GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

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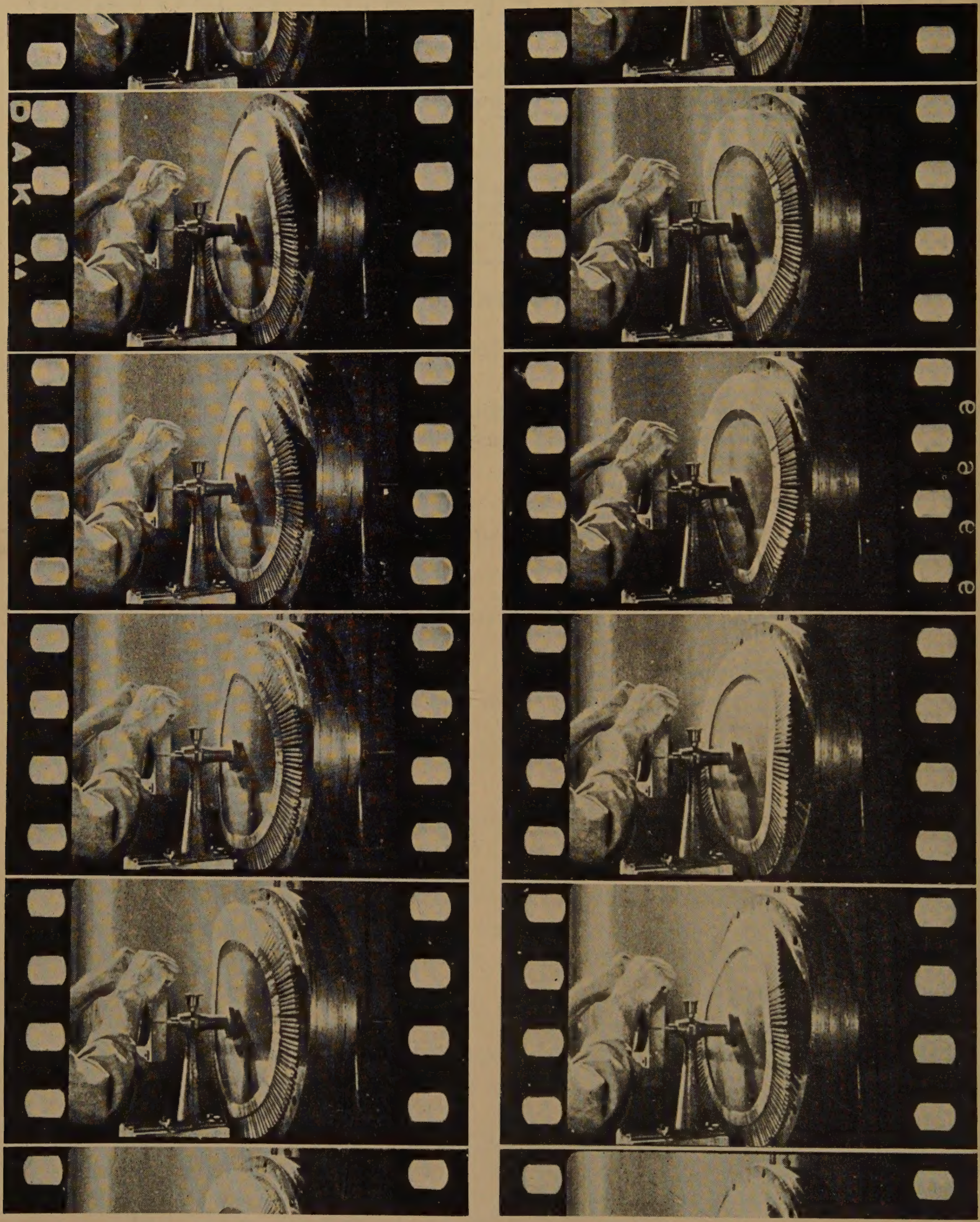


TRAVELING WAVE IN A THIN DISK MODEL OF A TURBINE WHEEL

High speed motion picture of a 4-node wave traveling backward one-half revolution in the wheel which is clamped stationary. Alternate exposures have been omitted in this reproduction. (See page 459.)

GENERAL ELECTRIC REVIEW

> *"Tongues in trees, books in the running brooks,*
> *Sermons in stones, and good in every thing"*
>
> *As You Like It. Act ii, Sc. 1.*

There is a certain school of idealists, devotees of the simple life, who deplore our present civilization as materialistic, superficial, and soul-destroying. They picture mankind as a Frankenstein, doomed to destruction by the mechanical monsters he has created to serve his desires. They say that his automatic machines, by their deadly monotony and through their very efficiency, have killed the wholesome interest and joy in work, and have created the restless need of stimulant and excitement; so now we have faster and faster trains, automobiles, and even airplanes, to accelerate the pulse of life, and motion pictures and radio incessantly to tickle our jaded nerves and to leave us no time for restful sober thought. And to meet this enormously increased strain there has been no corresponding mental growth. The best minds of today in no way surpass those of Plato and Aristotle. Man cannot control the machine he has created, but, as in a runaway motor car, is being carried swiftly to destruction.

It is a black picture, but it is black simply because, although the shadows have all been painted in, for the most part truthfully, the highlights have all been left out.

These machines and mechanical devices, which have developed and so marvellously multiplied in the last few decades, are not the whole story. They are but the partial manifestation, apparent to all, of a development and multiplication far larger, and far more important,but realized by relatively few. This lack of realization is the inevitable consequence of the very magnitude of the development. The departments of scientific endeavor have become so many, so highly specialized, even to their vocabularies, so prolific in their experimental data, that no man, not even he whose life is devoted to science, can maintain more than a fragmentary knowledge of the advances in fields of research other than his own.

Great as has been the growth of our material wealth, the growth of our mental wealth has been greater. Machine tools have increased, but the mental tools of science have increased far more. Back of nearly every material development lies a mental development, new knowledge, the result of research, usually of much greater moment than the device that applies or embodies it. Radio broadcasting has brought employment to thousands, and entertainment and instruction to millions, but the new knowledge that made it possible is having far more important results. A part of that new knowledge was the discovery of the electron, which has revolutionized the physical and chemical sciences and is carrying us far into the secrets of the constitution of matter and the mechanism of energy in all its forms.

As long as the growth of knowledge keeps ahead of the practical applications of it, we need not fear the overwhelming of the mental by the material. Not only has the scientific advance far outstripped its commercial applications, but its acceleration is greater, so that it is continually increasing its lead. There is no apparent limit, for each advance widens the unexplored horizon. Moreover, each discovery in new fields reveals overlooked possibilities in the old. In practically all known phenomena, from the simplest to the most complex, there are still rich opportunities for further research.

This is well illustrated by the article in this issue on "The Vacuum—There's Something in It." To seek for anything of value or of interest in vacuum—by definition "a space devoid of matter"—might seem at first glance as sensible a proceeding as prospecting for water power in the Sahara Desert. No better example of the universal opportunities for research could be adduced than Dr. Whitney's summary of the rich results of research in high vacua.

L. A. Hawkins

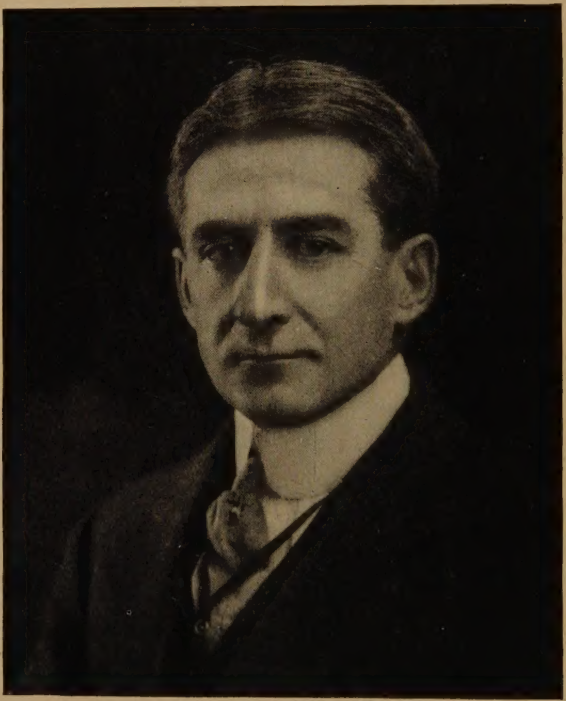
The Engineer's Place in Society

By Gerard Swope

President, General Electric Company

After a little pen sketch of barren places made fertile and waste wilds turned into the habitations of man by the work of the engineer, the author talks about the position the engineer should occupy in society. The engineer's training and his daily task are so conducive to the development of sound analytical judgment, which is so urgently needed in solving the many problems of our modern complex society, that we welcome the following authoritative statements of Mr. Gerard Swope on this important subject. This article, except for the omission of introductory remarks, presents the first Aldred lecture delivered before the students of the Massachusetts Institute of Technology.—Editor.

Up in the woods and wilds of Canada, a wonderful country of pines and rocks, where I had been camping some years ago when it was only a wilderness, there was a large waterpower, some 600,000 horse power, constantly going to waste. Through Mr. Aldred's vision and leadership and courage, and common sense if you will, this water power has been harnessed. Now, let us see what that has done. The wilderness has been transformed into a habitation of man. There men have reared their families; schools and churches have been erected, and a community has been founded where before only animals played. Constructive industries have been placed there, paper and pulp mills and works of a metallurgical character. But more than that, these industries have not only done things for that particular community where men and women are now living in happiness and contentment, but also they are sending their products out to the world and making it possible for human beings to seek and to find more than they ever had before.



GERARD SWOPE

It is a great contribution of one man to human beings and to the community of which he is a part. It is really great constructive work. It has taken vision; it has taken imagination; it has taken great courage, and it has taken common sense in the working out of the details.

So that today from a possible source of some 600,000 horse power, approximately 300,000—about half—has been harnessed for the useful work of man. That is the work Mr. Aldred has done. That, it seems to me, is the reason why it is so fitting that he should have inaugurated this course, giving to men who can go out in life to do similar work an ideal which makes for inspiration and makes for service to human beings.

As I traveled over the country this spring in the course of my work, I found other instances of constructive work, and I am going to speak of one or two, not because they are exceptional or alone, but simply because they carry a message to me and I hope they will to you. If they do not it is the telling that is wrong, because I think the idea is there.

I am going now from Canada, around Quebec and Montreal and the St. Maurice River, down into southern Arizona. There it is not a big engineering project. It is not nearly so large as the projects I have been speaking of in Canada that Mr. Aldred founded, but it has done something else. I speak, of course, of the Roosevelt Dam. In this case it was the courage and vision of the government engineers who saw the possibilities. The whole country there was an arid desert on which nothing could grow. The soil is one of volcanic formation, so that all it needs to be productive is water. Maybe I am saying things that are trite and that you know perfectly well, but I am going to hasten over them and give you a few of the points simply to carry the thought.

The rainfall in that region is about eight inches per year, insufficient for anything to grow except the cactus and the sage brush. So they built a dam 299 feet high, which contains the water gathered from the mountains and hills in back of it, to form a lake some 25 square miles in area which collects this 8-inch rainfall from about five million acres. The dam lets out the water and irrigates, at present, about 200,000 acres, giving an annual water supply of about 40 inches for each of these acres. The line of demarcation between the land that is irrigated and the desert land that is not is as sharply defined as the edge of this table. Where the water has come vegetation of various sorts—alfalfa, cotton and fruit—thrive and flowers bloom in great profusion and great beauty, and on the other side it is as arid as it was for centuries and centuries before. Into this valley have moved hundreds and thousands of people, who are now cultivating the soil. They have erected comfortable homes and are rearing their families in comparative comfort, because, of course, the water that is coming over the dam goes through waterwheels and produces electricity; so the dam is not only furnishing the water for irrigation of this region, but also producing power for industries—there are copper mines near there—and power and light on the farms. The people that are living in these homes have the comforts that you have in Boston, so far as electric lights and other appliances go. The people working on the farms have more appliances than the people who are working on the farms in New England. It is simply because this cheap power has been created. The amount of money that these works cost was not very great; some millions of dollars, twelve, I think, that was defrayed by the Government. The people who are using this water now are paying so much per year per acre-foot of water, which is sufficient to pay for the cost of the management of the enterprise plus the interest and amortization of the bonds, so that after a certain period the entire bonded indebtedness and the money that the U.S. Government put into it will be paid back.

But furthermore—and this is really quite instructive—the Water Users' Association of the territory has its own management and its own engineers. They have seen the possibilities, and now sixty-five miles below they are building another dam so as to accumulate the waters between the first dam and the second, very much as they do in the different water power developments on the St. Maurice River, or any great power development. Here, of course, they are planning primarily for irrigation and not for power, so they are getting the water from this watershed of sixty-five miles between the two dams, hence they can irrigate a greater area and supply a greater number of people.

Now what this has done, it seems to me, is this: First, it has made a part of the earth's surface habitable which was never before habitable. It has made it useful for the purposes of man, which it never was before. And, second, the products of that territory are now going for the use of mankind to other states, and it has produced those products at a lower cost, making possible a wider distribution. That, it seems to me, is another type of a great constructive enterprise—one that has brought comfort and a greater amount of well-being not only to the people who are cultivating the soil but to the people whose needs they are serving.

From there I am going to turn for a moment to the Northwest—and I am taking these various illustrations, not because they are comprehensive, or typical, but simply because they have come within my horizon as I have traveled over the country. Up in the Northwest, where they are handling great logging operations, I went to a paper and pulp mill of the character of those Mr. Aldred has made on the St. Maurice River. Great logs come in and are handled by machinery; no human hands touch them, and could do little if they did, they are so huge. I talked to a gentleman who had been fifty years in paper and pulp mills, first in the East and then out there, where he had come as a pioneer in the development of the business. He told me a story, which seems to me worthwhile telling here, for it is filled with much of import to us. I am not going to speak of the process of paper-making; I assume that you know it, or at all events, you know the last process, in which the pulp, held in solution in water, passes in a thin film between the rollers and the water is squeezed out so that finally the wood fibers adhere to one another and form the finished paper. The essential thing is that these rollers should run in synchronism so as not to put any undue strain on the weak fiber of paper as it is running through them. This man told me that they formerly ran their machine at about fifty feet a minute. He says he remembers the time when the superintendent suggested that they run it sixty feet a minute. That was a revolution in the shop; it had never been done; they couldn't do it; things would break down; you never could make paper that way. But to make the story short, it was done, and done successfully. But the interesting thing is that today they are running a thousand feet a minute with synchronous electric motors. They produce better paper, and twenty times as fast.

The point I want to leave with you is this: by this increased production—twenty times as great—a thousand feet a minute against fifty, you have done several things. You, of course, have cheapened the cost of your paper. Now cheapening the cost of paper has a tremendous significance, especially in a country like our own, where its democracy, if it is to be successful at all, must be founded upon education and the elimination of illiteracy among its people. Therefore, when you have made the production of the paper upon which your textbooks and your newspapers and your magazines are founded much cheaper, they can have a much wider distribution and reach a larger number of people.

It seems to me that that is the test of progress in civilization. Progress in civilization is a constantly larger number of people participating in its benefits. The test of a civilization must be the happiness, contentment and well-being of its people. If it is not that, it is not making the contribution to human beings that they can rightfully ask that a civilization shall make.

Now these are a few typical examples. After I happened to think of them and of speaking of them to you, I thought I would look up the definition of an engineer. That seemed to be a common-sense way of approaching this subject. So I looked in the dictionary. Possibly my dictionary was out of date. I have asked to see others, because I couldn't believe it; it is a Webster's Dictionary a few years old; there may be more modern ones now. It says: "An engineer is one who manages a stationary or a locomotive engine." That is all it said. There wasn't any other definition; there wasn't any other thought. Below that it said, "Engineering is the art of managing engines; especially the art and science by which the mechanical properties of matter are utilized in the construction of machines." And that is all of engineering.

Now, of course, to your mind and to my mind both engineer and engineering have a very much broader significance than that. If Mr. Aldred had not spoken first I might have said some of the same things—though not as well as he did. But I wish to speak of the following facts which, it seems to me, underlie engineers and engineering.

First, you have to analyze your problem: What are its elements? You use your mathematical analysis to break down your proposition into its simplest elements and see what those elements consist of. There is no more exact method than mathematical analysis. It is accurate; you can depend upon it when you have it. That is a fine thing in engineering—its basis is a thing you can depend upon.

Now after you have that analysis, you have to apply common sense in the interpretation of it. This is where it seems to me that common sense, which is common and still so uncommon, as Mr. Aldred has said, comes in. It is your sense of value, it is the sense of proportion of these various elements that your analysis produces. You can have an analysis of a problem presented to six different men and the six different men may see it from six different points of view and not any one of them, possibly, get a comprehensive view of the relation that the different elements bear to each other, which it seems to me quite essential that we grasp before we can proceed to a comprehensive solution of what the problem involves.

Then after you have your analysis, you have to have another thing—and this I have found, too, in my own experience, as you also have found or will find in yours—after you have your analysis and after you have made up your own mind as to what the proper balance of these elements is, you have to have the courage to make a decision. It is perfectly remarkable in life how many people like to pass the "buck"; how often they would rather have the other man make the decision. People often feel that if they have someone else make the decision they are relieved of it and so avoid mistakes. In other words, you have got to have courage in making a decision. It is not so much a conscious courage as it is faith that you have made your analysis correctly, that you have placed the proper valuation on these elements and then say, "Yes, that is the result of my analysis and I am going to go ahead along that line," and then go ahead. Of course you will "come a cropper" occasionally, as the successful man, as Mr. Aldred says, "comes a cropper" occasionally. We don't speak of them very often.

Mr. Aldred has accentuated the difficulties and the pitfalls. I want to accentuate the high points from which you can look out and see the opportunities for service in this great profession that you are embracing.

To my mind there is no better basis for human work than study along engineering lines, because it trains in exact analysis. If you will give to the engineer also a cultural training, so that he has something of the history of the development of a people, of its civilization, of its tendencies—so that he can look upon social movements as they arise with some tolerance and also with sympathy, because one needs sympathy in life—then it seems to me that the engineer is the best fitted of any profession to grapple with the problems of life.

And that leads me to my next thought, for I think that engineers have done least of all in the solution of the problem before our social fabric, which is the industrial problem. A comparatively new situation is the factory development of industry, where you have a large aggregation of capital in the form of a corporation, and large numbers of people employed in the service of that corporation, and the questions of management arising. It is not really a question between capital and labor; it is largely a question between management and labor. I am as much an employee of the General Electric Company as the janitor or the porter. I don't control the corporation, I am free to confess. I am a stockholder in it, but a very small stockholder. There are many, many larger. There are very few corporations which are owned or controlled by one or two men. They are usually owned and controlled by thousands and thousands of stockholders in all parts of the country, and often a large part of the stock is held by the workers themselves. So the problem in industry is not a problem, as it seems to me, between labor and capital, but between management and labor, where management is also as much of an employee as the laborer himself.

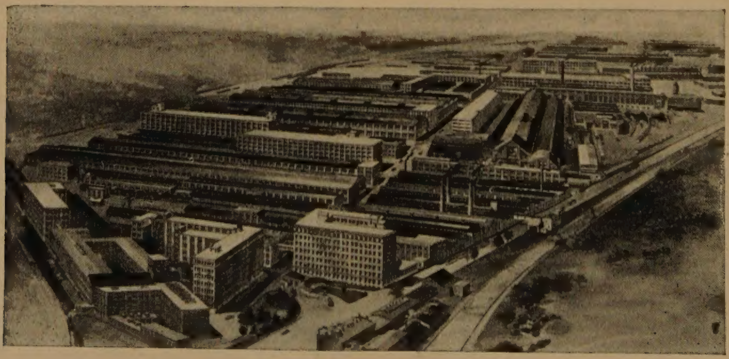
Now it is largely a question of approaching that problem, as I said, with justice and with sympathy to find the right solution. And in this the engineer has taken but little part. He has been very largely an academic adviser. He has not gone into the hurly-burly of the work to find the right solution, or how the problem should be handled to work out the best results. It is an engineering problem. You have thousands of men engaged on work that is worth while doing for the community, that should win their respect, constructive in every way, and of a character that should appeal to their imagination; and still largely we regard it as a task to be performed. We eliminate from it all the individuality and the personality that must go with it if they are to retain their self-respect and have ours. It seem to me engineers can make a contribution toward a correct solution of this problem which is needed very much indeed.

And there is one other point. I think one indication of the civilization of a country is the wages it is paying to its workingmen. There is nothing inconsistent between high wages and low costs, because what you have got to see to is that your high wages are more largely productive. Now that is largely an engineering question; first, engineering in a constant search for truth and for better methods of production, introduction of automatic machinery, introduction of labor-saving devices, since it is a constructive thing in the interest of society to eliminate human labor and to replace it by machinery; which labor will admit. Of course, the transition stages sometimes work a hardship upon the labor immediately engaged; but as far as labor themselves and society as a whole is concerned there is not a doubt that if you can reduce human effort by the introduction of machinery you have set up another milestone in the progress of human beings and of the community as a whole. So that it is not at all inconsistent, as I say, that you should have low costs and high earning power on the part of your men. But it does mean on the part of engineers an increased responsibility to find constantly better ways of doing things.

I am going to illustrate this by some work that has been done by the General Electric Company, who have been pioneers in the development of the incandescent lamp. The primary invention of the incandescent lamp was of course Edison's, but the later work is particularly associated with three brilliant men, two of whom are Tech men—Dr. Willis R. Whitney of the class of 1890, and Dr. William D. Coolidge of the class of 1896; and there is another man, Dr. Langmuir—but he doesn't happen to be a Tech man, so I won't mention him—also of the General Electric. They constantly set themselves the task of finding a better light with less energy and therefore at less cost to the community, so that a larger number of people might enjoy its benefits. They have solved this problem and their inventions are now the basis of the art throughout the world today. But the thing that has been done subsequent to this work is the application of engineering methods to the problem which was then left—that is, the problem of working out those methods to the best advantage. This has been accomplished by the introduction of automatic machinery. Almost within the last year the industry has been revolutionized, and now we are on the way to getting a much greater output per operator with less effort, a much greater output per square foot of floor space, and a much greater output in number of lamps per thousand dollars of capital invested. From every point of view it is a great constructive forward step in having introduced better methods, more automatic machinery, decreasing the labor content and therefore decreasing the cost by increasing the output for a given amount of effort, and finally resulting in lower prices to the public, thereby reaching a larger public than before.

Now we see what that means. It is the application of pure engineering, of pure common sense, to the problem. This has not been done by any one man; it has been done by a group of men working to solve the general problem. I speak of the work in the lamp field because it is typical. The same thing is going on in all industries. It is going on in the production of motor cars, in the production of motors, dynamos and many other things. Wherever engineers are applying their minds to the problem of doing better work, where they are showing that decreased cost of production is not incompatible with increase of wages to labor, they are helping in the general progress of humanity.

When the problem of establishing better relations between labor and management is solved, and the men find greater pleasure in the work they do, and receive remuneration commensurate with the service they are rendering, the engineer will have performed his greatest service. The engineer's training fits a man perhaps better than any other profession for this service to the community, this broad service to society. This tremendous field lies before you, and in service of that character any human being is going to find the best satisfaction and the greatest happiness. In other words, you can all make contributions that reduce human effort in the production of useful articles, making them at less cost, which means they are available to an ever-increasing circle of people, adding to their comfort and well-being, which spells progress to civilization. It is the finest contribution that the engineer can make to the solution of the problems of society.



Schenectady Works, General Electric Company

Switchboard Type Temperature Indicators

By D. M. Carswell

Switchboard Engineering Department, General Electric Company

The electrical industry is to be credited with an earnest and continuous endeavor not only to extend the usefulness of electric service but to render that service economically. One of the elements essential to the latter purpose is the loading of the equipment to its maximum safe capacity. To give operators confidence in this method of operation, by lessening the risk of their inadvertently crowding their equipment too much, convenient temperature indicators have been developed. These indicators provide an accurate and reliable means of keeping posted on machine temperatures, and thus overheating is practically inexcusable.—Editor.

The maximum hot-spot temperature is a matter of great importance in the operation of rotating electric machinery and of transformers. Apparatus ratings are determined largely by a consideration of the temperature rise and the safe operating temperature for the insulating materials used. The standardization rules of the American Institute of Electrical Engineers set the limits of permissible temperature in various parts of electrical apparatus and describe the methods to be used in determining temperature.

The following three methods of temperature measurement are in common use when heat run tests are made:

(1) Thermometer
(2) Resistance
(3) Embedded temperature detector.

Usually the principal method employed is checked by one or both of the other methods when making the test.

Mercury or alcohol thermometers can be placed only on external points and it is customary to add a correction factor of 15 deg. to the highest temperature observed in order to approximate the actual "hottest-spot" temperature of the machine. This is the accepted method for small machines.

The resistance method consists of measuring the resistance of the winding at ambient temperature and after the heat run, and then of calculating the temperature rise from the rise in resistance and the temperature coefficient of copper. This is the accepted method for transformers and induction regulators.

The A.I.E.E. Rules require the use of embedded temperature detectors for the stators of all machines above certain specified sizes.

Because of the fact that the life of insulating materials depends on the temperature to which they are subjected, the operating engineer is concerned to know as nearly as possible at all times the temperature of the hottest spot in the winding of his apparatus in order that it may not be damaged by overheating. This is especially important during periods when it is necessary to operate the apparatus at an overload.

Obviously, methods (1) and (2) are not well adapted to show continuously the temperature of machines or transformers under station operating conditions. To meet these conditions there have been developed, for use with embedded temperature coils or detectors, switchboard types of temperature indicators which are reliable in operation and by which the temperature readings may be readily taken with a minimum of manipulation.

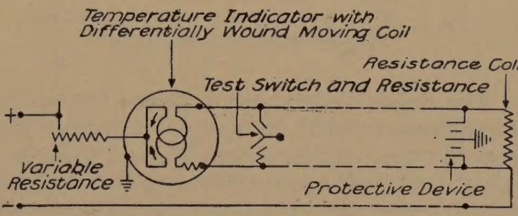

Temperature Indicator with Differentially Wound Moving Coil
Resistance Coil
Test Switch and Resistance
+
Variable Resistance
Protective Device

Fig. 1. Scheme of Connections for Direct-current Type of Resistance Detector

There are two general classes of temperature detectors, the resistance coil and the thermocouple. In either class the detector elements are embedded in the windings as near to the copper as is practical, so that they will follow closely the changes in temperature at the points selected.

EQUIPMENTS FOR ALTERNATING-CURRENT GENERATORS AND MOTORS

Resistance Detector, Direct-current Instrument

This type of indicator is a differential D'Arsonval instrument, one winding of which is connected in series with a resistance coil having a zero temperature coefficient and the other winding is in series with the copper temperature coil embedded in the stator winding. The diagrammatic arrangement of the circuits is shown in Fig. 1. A direct-current operating source is employed and the instrument is calibrated for a balanced condition of its coils at approximately 80 deg. C. when a given potential is impressed.

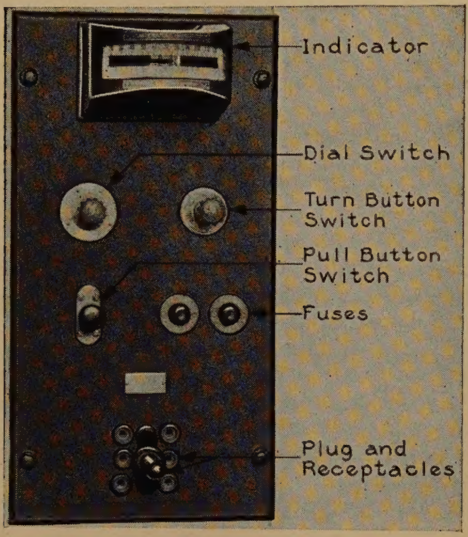


Fig. 2. Direct-current Type of Resistance Detector Mounted on a Switchboard Panel

The resistor connected between the operating circuit and the indicator is provided with several taps corresponding approximately to 5 per cent voltage variations. For accurate readings the tap used must be the one which corresponds most nearly to the voltage of the operating circuit at the time the reading is taken.

The temperature coils are made of copper wire wound on a thin form and pressed flat so that they occupy very little space. These are adjusted to have a definite resistance value, usually 10 ohms at 25 deg. C. Three leads of equal size are used between the temperature detector and the indicator, in order to avoid errors in indication due to the temperature changes to which the leads are subjected.

The total lead resistance is also a factor in the instrument calibration, and a re-calibration should be made when for any reason the lead resistance varies materially from the value for which the instrument was calibrated.

The number of temperature detectors used varies usually with the size of the machine, four for the smaller machines, six for larger units, while for the largest units (25,000 kv-a. and upward) ten or more detectors may be employed. These are located at different points in the windings where experience has shown the highest temperatures may be expected. The greater number of these will be found between coils in slots although two or more may be at the bottom of slots. It is generally satisfactory to select only two or three of the detectors, which by test show the highest temperature, for operating the switchboard indicator.

A protective device consisting of a pair of film disk cutouts for each temperature detector is mounted on the machine frame. Any excess voltage due either to an accumulation of static or to a breaking down of the insulation of the stator winding will cause the puncture of a film to the ground connection, which is between the pair of films, thereby affording protection to the instrument equipment and to the operator.

Fig. 2 shows the complete equipment mounted on a switchboard panel; and Fig. 3 shows the wiring diagram for the panel. Referring to Fig. 2, the method of making a temperature measurement is as follows: Turn the turn-button switch to the ON position, thereby completing the circuit to the direct-current operating circuit through the fuses. Operate the dial switch to connect to the correct resistor tap. The receptacles and plug are used to connect in circuit the temperature detector whose temperature it is desired to observe. The indicator will then give a direct reading of the temperature in degrees centigrade. No further manipu-

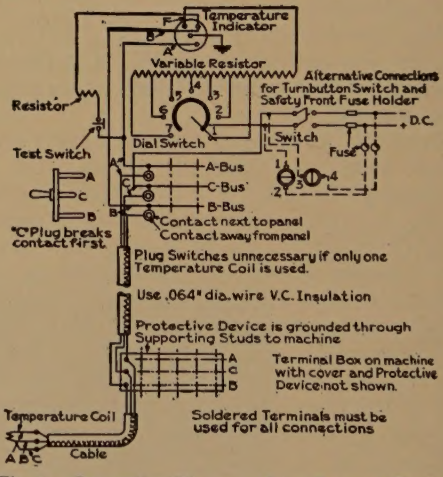

Temperature Indicator
F
B
A
Variable Resistor
Alternative Connections for Turnbutton Switch and Safety Front Fuse Holder
Resistor
1
2
3
4
5
6
7
Dial Switch
+ D.C.
Switch
Fuse
Test Switch
A-Bus
C-Bus
B-Bus
A
C
B
"C" Plug breaks contact first
Contact next to panel
Contact away from panel
Plug Switches unnecessary if only one Temperature Coil is used.
Use .064" dia. wire V.C. Insulation
Protective Device is grounded through Supporting Studs to machine
Terminal Box on machine with cover and Protective Device not shown.
Temperature Coil
Soldered Terminals must be used for all connections
A B C
Cable

Fig. 3. Connection Diagram of the Detector Equipment Shown in Fig. 2

lation is necessary to obtain the correct reading continuously unless the operating circuit voltage fluctuates. In case it is desired to check the operating condition of the indicator, the pull-button switch may be operated thereby connecting a test resistance across the coil circuit and giving a certain deflection of the needle.

THERMO-COUPLE INDICATOR EQUIPMENT

This type of indicator makes use of the fact that a difference of electrical potential exists at the junction between certain dissimilar metals. In a closed circuit made up of leads of two dissimilar metals there will be two junctions. If both junctions are at the same temperature the e.m.f's. will be equal and opposite so that no current will flow. If however one junction is at a different temperature than the other, there will be a difference in e.m.f's. which, for the range of temperature encountered in electrical machinery is proportional to the difference in temperature.

In these equipments, referring to Fig. 4, thermo-couples are embedded in the stator windings in a similar manner to the placing of resistance temperature detectors already described. The temperature indicator is a D'Arsonval instrument operating on the current necessary to produce an e.m.f. across a constant resistance to balance the e.m.f. set up between two wires of different materials when one junction is exposed to the temperature to be measured and the other junction, or the "cold end," is kept at a known temperature. The condition of balance is indicated by the zero reading of a galvanometer. The "cold end" is maintained at a constant temperature usually 40 deg. C. by means of a heater and thermostat in the cold-end junction box, a standard 15-watt switchboard indicating lamp being used for the heater. The battery is a single dry cell and the current is adjusted by means of a potentiometer.

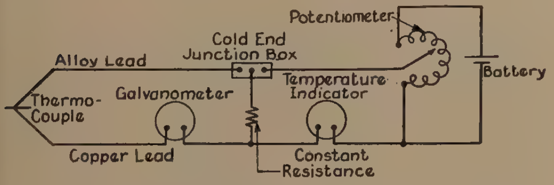


Fig. 4. Scheme of Connections for Thermo-couple Type of Indicator

Fig. 5 shows an equipment mounted on a benchboard slab. It will be noted that a leveling base was used for the galvanometer to compensate for the angle at which the slab is mounted. In this case the dial switches provide for selecting any thermo-couple in any of three alternators. When a reading is to be taken the temperature shown by the thermometer in the cold-end junction box should be read and any variation from the 40 deg. calibration temperature noted. The temperature indicator pointer should stand at the balance point and the galvanometer pointer at the zero position. Then closing the main switch and adjusting the potentiometer to obtain zero indication on the galvanometer, the temperature in degrees centigrade is read directly on the indicator scale.

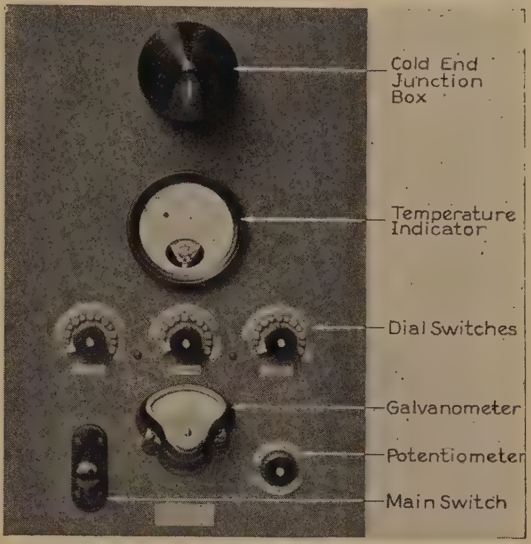


Fig. 5. Thermo-couple Type of Indicator Equipment Mounted on a Switchboard Slab

The main switch is of a double-throw type and is to be pushed in for reading temperatures above 40 deg. and pulled out for reading temperatures below 40 deg. The reading obtained should, however, be corrected by adding or subtracting the variation, if any, in the temperature of the cold-end junction box.

The cable from the switchboard to the terminal board of the machine must contain one copper lead for each thermo-couple and one common alloy lead. It is imperative that the material of these leads be the same as used in the thermo-couples.

EQUIPMENT FOR TRANSFORMER WINDINGS

Resistance Detector, Alternating-current Instrument

For observing the temperature of transformer windings, a somewhat different principle of operation has been adopted from

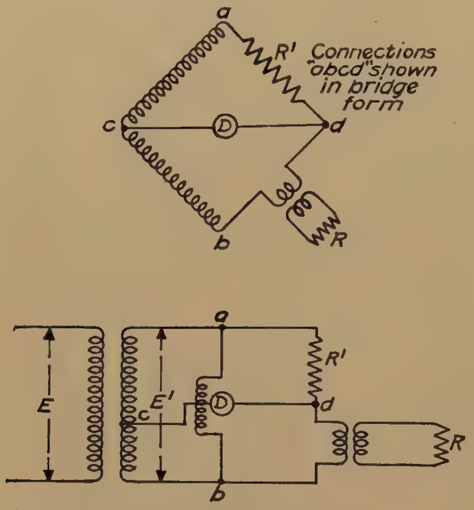


Fig. 6. Scheme of Connections for Alternating-current Type of Resistance Detector

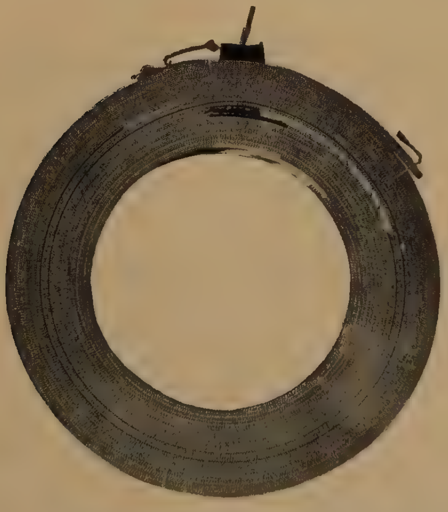


Fig. 7. Disk Winding with Temperature Detector (two dark lines) Embedded Between Parallel Conductors

that used for generators because of the difficulty that would be encountered in insulating the embedded temperature coils.

The indicator operates on the dynamometer principle. It is connected to a potential transformer with suitable resistances arranged in the form of a four-armed bridge, as shown in Fig. 6. Two arms of the bridge *ac* and *cb* are formed by the secondary winding of a potential transformer, the third arm consists of a constant resistance, while the fourth arm is the primary winding of an insulating transformer whose secondary is connected to the non-inductive temperature coil. By applying a voltage *E* to the primary winding of the potential transformer, a secondary voltage *E'* is obtained at the points *a* and *b*. Between these points there are three circuits, two of which *acb* and *adb* form the bridge while the third *ab* is the fixed coil circuit of the indicator. The bridge is adjusted for a balanced condition when the temperature of the coil *R* is approximately 90 deg. C. The indicator scale is calibrated to indicate the temperature directly in degrees. As the temperature of the transformer winding changes the resistance of the temperature detector changes, thereby affecting the balance of the bridge and actuating the

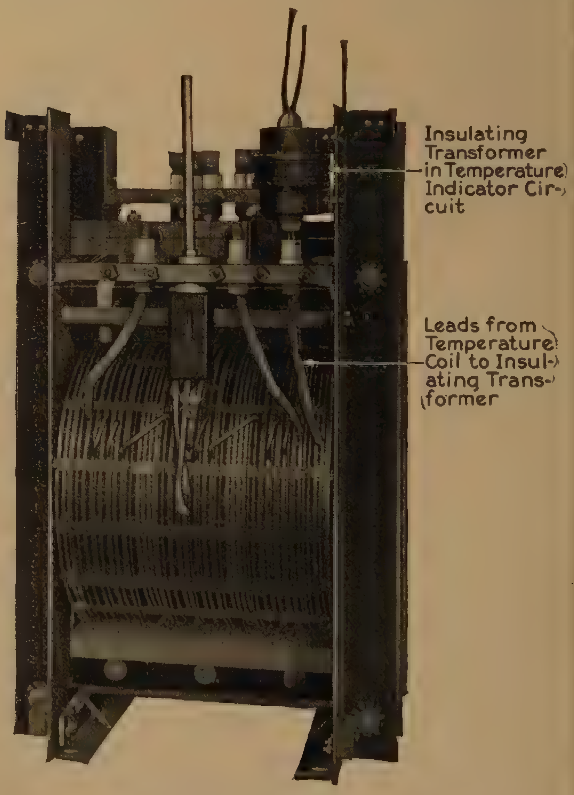

Insulating Transformer in Temperature Indicator Circuit
Leads from Temperature Coil to Insulating Transformer

Fig. 8. Assembly of Power Transformer, Showing Location of Insulating Transformer

movable coil of the indicator causing a deflection of the pointer to read the actual temperature of the detector.

The temperature detector consists of an insulated flat copper core about which are non-inductively wound two insulated copper wires. The unit is about 20 ft. in length and is always inserted between parallel strands of the same potential. Fig. 7 shows the general method of embedding a detector between the strands of a disk type transformer coil.

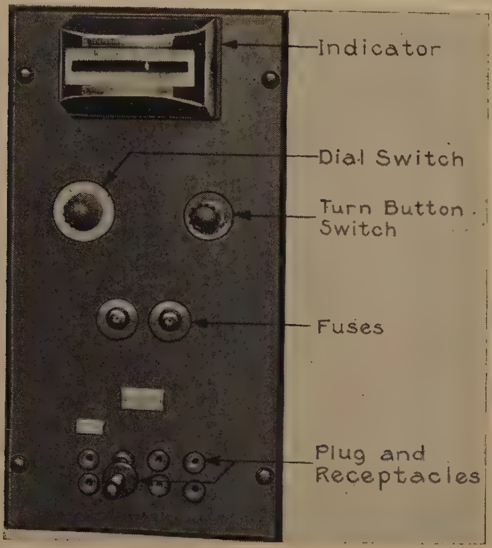


Fig. 9. Alternating-current Type of Resistance Detector Equipment Mounted on a Switchboard Panel

The insulating transformer, which is indicated in Fig. 8, provides the necessary protection from the high potential of the transformer winding.

Variations in the size and length of the leads used between the transformer and switchboard are compensated for (up to a total of 1.5 ohms) by selecting the proper tap on resistance *M*, Fig. 10.

Fig. 9 shows the complete switchboard equipment mounted on a small panel; and Fig. 10 shows the panel wiring diagram. Referring to Fig. 9 the manipulation of the panel is as follows: Turn the turn-button switch to the ON position, thereby completing the circuit to the alternating-current operating source through the protective fuses. Set the dial switch on the transformer tap corresponding most nearly to the voltage of the circuit. The plug may be inserted in one receptacle to connect in resistance *D*, Fig. 10, in order to check the operating condition of the instrument or in either of the other receptacles to read the temperature of any temperature detector. When so connected the indicator will give a direct reading in degrees centigrade of the temperature at the point where the detector is located. No further manipulation is necessary unless there is a change in the operating circuit voltage, which requires that the dial switch be moved to the proper tap.

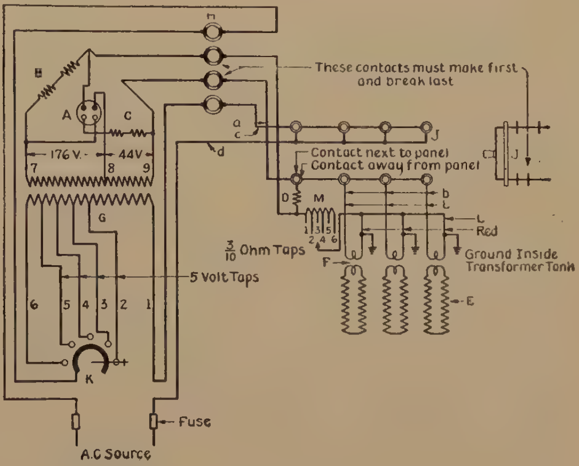


Fig. 10. Connection Diagram of the Detector Equipment Shown in Fig. 9

The Vacuum—There's Something in It

By Dr. W. R. Whitney

Director, Research Laboratory, General Electric Company

The contents of this article were originally presented in an address delivered by the writer before the American Association for the Advancement of Science, at Cincinnati, December 28, 1923. Its purpose was both to inform and to encourage workers in other scientific fields, by presenting a summary of the results of research in what might seem the most unpromising field of all—high vacuum.—Editor.

We humans want better minds, broader horizons, and greater understanding. Scientists everywhere are at work in their respective fields searching for new truths to improve the process by which our minds, our horizons, our powers, and our outlooks grow.

When, in the middle ages, the great cathedrals of the world were being built, the mentality of men seems to have been directed to systematic subordination of creation rather than to active appreciation of it; to acquiring salvation, or "safety first," rather than knowledge or understanding. Today scientists, in seeking truth, think of "safety first" last.

We are told that if the total age of mankind be expressed as the life of a man of fifty years, and if he then looks back upon his progress, he will see that what marks his greatest advancement are events occurring in the most recent years. For example, such a fifty-year man now sees that he had not learned to scratch the simplest records on stone until his forty-ninth year. All the immense advantages of printing have existed only three months for him. He has only just learned how to pass along what he has learned. The uses of steam, which now seem so necessary, were acquired only three or four days ago. The uses of electricity (street cars, lamps, and telephones), which did not actually begin until about 1880, arrived the day before yesterday to this fifty-year man. The automobile, radio, X-rays, radium, and most of the things which occupy our interests today, were actually discovered on this particular fiftieth birthday.

The power outside of his own muscles, which during the past two or three months he has learned to control, has grown to nearly twenty horse power, or two hundred man power, for every man in the country. Therefore it makes only one half a per cent difference whether all the men work like horses or not. But *guidance* of power is man work, because there are no machine mentalities. Almost everything but thinking may be artificially done, but knowledge and understanding must be actively sought and used. Man is the only animal that can do this.

Scientists know that research merely discloses new parts of the infinite unknown. Paradoxically, the enticing, helpful "unknown" increases as men continue to subtract *from* it. Progress in every line of experimental science follows the same law. The apparently narrow path gradually expands into unlimited, unexplored territory. With his new tools and his increased speed of communication, man finds that he can advance into the unknown faster than his ancestors could, and children seem to learn more rapidly than he did when he was young. The scientists of the twentieth century are legion. But scientists were anathema a short time ago. There is today more chemistry in the atom than there was in all "inorganic" chemistry a few years ago. There is more in the "sugars" now than there was in all "organic" when the writer studied it. There is more immunity in blood, and more heredity in the microscopic chromosome, than there was in all biology until recently. There is more crystal structure research by X-rays now than research in all mineralogy when Agassiz came to America.

In the preparation of an article the purpose of which is to direct attention to the interest connected with research work in general, there is special reason for selecting as the subject such a narrow field as the vacuum. The writer wishes to show that in a vacuum, of which one might say "There is nothing in it" (and surely less than in anything else), there is, indeed, an endless amount of interest and utility. The American public now buys over a million dollars worth of glass vacua a week, but that is the least interesting part of the subject.

Everybody pretends to know that "Nature abhors a vacuum." But he who started that tale merely meant that a good vacuum was hard to produce. As probably no one has ever made a vacuum with less gas-molecules in a cubic inch than there are people in the world, we can maintain that perfection in vacua is still precluded by nature.

Some studies in vacua will now be reviewed so as to create the impression that any one may well do research work not only there but also certainly anywhere else with pleasure and profit.

We all know that we see at night largely by the aid of vacuum lamps. Through other vacuum lamps, called X-ray tubes, we also see through opaque bodies. The light which illumines our microscope specimen has its analogue in the X-ray light which shows us the crystal structure of matter and the electrical formulas of chemical atoms. Our trans-continental wired telephony is possible through vacuum tubes which, in various forms, also permit our radio broadcasting and radio reception from the most remote stations. The workman who keeps his drink hot or cold in a thermos bottle is clearly indebted to Sir James Dewar's application of the vacuum but the scientist is still more indebted to it. All our steam power plants, including turbines, owe their success to vacua.

The latest arrival in the family of the chemical elements (hafnium) was discovered by trying it in vacuum as an X-ray target. Our list of possible chemical elements was rounded off by Moseley's study of the X-ray spectra just in time to meet the wonderful discoveries of J. J. Thomson and Aston, all made in vacua. The latter showed that most of the elements, supposedly simple, are still mixtures of two or more similar elements (isotopes), while Professor Thomson's experiments disclosed by the positive ray method a whole series of new atomic compounds.

While the vacuum was not essential to the work of Millikan in isolating the electron, yet the earlier work by Thomson and others, and much of the recent work on this ultimate constituent of matter, has been necessarily carried out in vacuum. Today there seems to be no end to the studies which can be based on the fact that an atom or molecule of material may be separated electrically into a positively charged ion (carrying most of the mass) and a negatively charged electron (carrying most of the current).

Electricity

Without sacrificing historical truth too much, it may be asserted that electricity at rest was the first kind known. It then seems logical that electricity in simple direct motion should later appear and that still later we should find various directions and rates of its motion, if it moves at all. It will interrupt this line of argument if we doubt the existence of electricity as a thing, or question the existence of such different kinds of it as static and dynamic. The electricity of rubbed amber was the first and stationary kind (if it is admitted that prior to Thales such things as lightning were something else). When electricity first moved through metals the process was looked upon as a simple directed flow which proceeded until the charged body had delivered its charge.

Currents

This direct flow of electricity (a current) was strengthened in its hold on our conception by the great number of different chemical current-producers which followed the controversies between Galvani and Volta a century and a quarter ago. Primary and secondary or storage batteries without number were soon discovered. The current from such batteries was exactly like that which the magneto-electric machines produced, when these were developed, after Faraday had shown the effect of moving a wire through a magnetic field.

The direct current of such generating machines was much later followed by the alternated flow, and soon alternating-current generators were made for different rates of reversal of direction. Sixty-cycle and twenty-five-cycle currents are now common and the user takes his choice. These frequencies were once accidents of convenience and economy. For some uses other widely different frequencies of alternation are very desirable, as in radio, where 1,000,000 cycles are common.

Now the phenomena which have been found in vacuum tubes promise to give complete control over all these details of kind and frequency of current.

Electrical Control

As will be more fully shown later, when a unidirectional current meets vacuum tubes as though it would pass through them, it must find one particular kind of a tube, and the current's direction must be right, because some tubes will let it through only when it is both unidirectional and in the proper direction. These in themselves are rather remarkable things to expect of a vacuum, but as usual the truth exceeds the expectation.

Catalysis

To give some idea of the extent to which vacuum studies may affect remote fields, mention may be made of chemical catalysis, the secret of most reactions of life. For example, it is known that mercury vapor in a vacuum, when illumined by light of a certain wavelength, will absorb that light and turn the energy over to hydrogen, if hydrogen be present, so that this, in turn, will chemically reduce such substances as cold copper oxide. Here is a new kind of chemical process. It is the kind we have needed in order to begin to explain some of those life-reactions which vegetation discloses. That is, similar facts will probably be found to contain the explanation of the catalytic action of sunlight on growing plants.

And so the studies of phenomena in vacua may lead us into the most widely separated fields. The experiments described in the latter part of this article are illustrations of this fact, and are thus not chosen to be very closely related.

Kinds of Vacua

One might say, as in our school-day essays, "There are different kinds of vacuum too numerous to mention" and then proceed to mention them all. However, only a few cases will be selected for the purpose of illustration. A certain kind of vacuum is good enough for incandescent lamps because other factors besides the quality of its vacuum determine the death, or limit the performance, of a lamp. But while formerly the incandescent lamp represented the very highest skill then reached in vacuum production, there are now other commercial vacua which are necessarily quite superior. This is true of good thermos bottles, X-ray tubes, and radio tubes.

We should first, therefore, give brief consideration to the incandescent lamp, and note a few characteristics. Its low vacuum early disclosed electric cross currents which would not have been found in much higher vacua. Study of these currents has led not only to the vacuum tubes used in radio, but also to such remote disclosures as that distillation or evaporation of solids in vacuum proceeds in straight lines. The electrical currents in poor vacua are best known in luminous Geissler tubes, Moore tubes, and Claude tubes, as seen on the streets of Paris, for example. They are themselves a large subject, but consideration will be given (later on) only to one historically important experiment with them, the Hittorf experiment.

High Vacua

Electric currents through vacua, where gas is so completely removed that it has no appreciable action, are more strictly a part of this article. After the work by which the individual and indivisible negative electrical charge or electron was defined, it seemed quite fitting, though unexpected, to learn that these negative charges were exuded by hot bodies. The result of this disclosure formed the basis for most of the modern electrical phenomena in vacua. The activities of electrons are apparently the cause of most electrical and chemical processes. Their motion constitutes electric currents, and the currents are determined and controlled by voltage or potential difference.

Bees might illustrate electronics, though it's admittedly bad policy to push bees too hard. If bees represent electrons, then matter in general becomes the hives. When the hives are cold or in the dark the bees stay inside. Under the effect of heat or light the bees are induced to come out. Similarly highly heated matter, such as tungsten, exudes electrons; and at ordinary temperatures light induces electrons out of metallic potassium, for example.

What are the bees or electrons going to do after they are out of the hive (or the metal)? That depends on impulse or pressure. They will fly in that special direction which tends to relieve that particular pressure. They proceed down the gradient. The electrons coming out of the metal (because of heat or light) will also fly in that special direction which will tend to relieve the particular electrical pressure. They also proceed down the gradient. But if there is no particular impulse or gradient both bees and electrons hang around the source.

A lot of electrons, like bees, flying in a common direction, becomes a current or cathode ray. We might let them fly from the hot or lighted spot into a cold or dark one, and until we heated or lighted the latter they would not come out. This unidirectional current corresponds to what takes place in rectifiers and kenotrons where we have impulses in two opposite directions between one hot and one cold electrode in vacuum. If the hives (or the electrodes) are equal in temperature or illumination, no differential in current is possible, and with alternating impulses alternating instead of pulsating direct current passes. Thus bees illustrate two-electrode vacuum devices.

In the three-electrode vacuum tubes the third electrode is a sort of grid, or open fence, located between the hot and cold electrodes. This grid lets electrons pass freely except when it is negatively charged. Thus also the bees would pass through a wire fence when they might be stopped if their impulse to proceed could be suddenly removed there. The negative charge is used in the three-element tube to alter the intention of the migrating bees or electrons as often as desired, and this with the rapidity of light.

In the case of radio, it is the impulse from the antenna or loop, changing with every delicate change of voice-current or code-current, which, when led to the grid, charges it and thus controls the currents within the receiving tube. These controlled currents do the work in the telephone.

Everybody knows that radio tubes are very sensitive. One cat-power of electricity used in New York actually puts the impulses into a receiving outfit in San Francisco, and at the same time it also puts the identical impulses into millions of other receivers. But some appreciable energy must be used by each receiver to direct the local battery which operates the head sets. This minute quantity of energy may be made significant as follows:

If a house-fly climbs up a window pane one inch, he does a definite amount of work in lifting his body that much. If this work constituted the supply fed into the receiving tube from space, it would suffice to actuate the outfit continuously for a quarter of a century. This might interest a future student of telepathy, if the time comes to determine how far the energy of one thought may influence thought in a distant brain. It has not been possible thus far to determine the quantity of energy which is expended in thought. Just keeping alive transfers so much energy into heat that the additional energy transferred when we think has been too small to detect. But it need not be small compared to the power sensitivity of a radio set.

Vacuum Tubes

The mere names of modern vacuum-tube applications of electrons are legion. The kenotron is a vacuum tube which changes high-voltage alternating current into direct current, and it has its counterpart for low voltages in the battery-charging tungar rectifier and the mercury rectifier. The various radiotrons, receivers, and amplifiers of radio are also the most direct applications of the action of negative electrons in good vacua. But X-ray tubes must also be considered in this connection, because X-rays are the result of the "bump," if you will, of rapidly moving electrons in vacua against the atoms of matter.

Electrons in motion are also directed and controlled by electromagnetic, as well as by electrostatic, fields. Therefore the magnetron and axiotron have to be included. Because the mere illumination of such metals as potassium (like the high heating of other metals, such as platinum and tungsten) causes them to emit electrons, the photoelectric cell has to be included in our illustrations.

The electrons within the vacuum, as in a radio detector tube, obey the inconceivably feeble electrical impulses received by the antenna. Conversely, the motion of electrons sets up impulses and waves in space. In other words, the vacuum detector may be made a radio wave generator. Such tubes are used in broadcasting stations.

Ether Waves

The wavelengths of the magnetic waves produced by the changes of motion of the electons are very long in the case of radio (say 100 to 10,000 ft.), millions of times shorter in ordinary light, and millions of times shorter still in X-rays, but they are all in the same medium and all due to motions of electrons.

Special Emissions

Finally, to give an impression of the distance such work has gone, there should also be added the case of a one-atom-deep layer of thorium on tungsten in a vacuum and its effect on electron emission.

EXPERIMENTS

Lamps

The first great use of vacuum was in incandescent lamps. If such a lamp is burned at much higher than its rated voltage, it lasts for a few minutes only, but it gives a light perhaps five times as efficient as we usually see. The lamp dies because the tungsten vaporizes or melts. The vacuum is not at fault. It is because of these limitations that commercial lamps are so made that they burn at normal voltages on proper circuits an average of one thousand hours. If we were satisfied with a shorter life we could have a more efficient lamp, but experience has shown that we would be unwilling to use the short-life lamps in order to secure the added efficiency. To increase the efficiency without shortening the life of lamps much study has been made of distillation of metals in vacua, and of methods for returning the distilled metal to the filament. Much has also been done to make the deposit on the glass invisible or white, so as not to interfere with light transmission. Naturally we are always on the lookout for metals, such as the newly discovered hafnium, which might possibly live longer as a filament than tungsten now lives. Thirty or forty years of research work had been spent on high-vacuum incandescent lamps before Dr. Langmuir showed us how to make still better lamps by putting back into the vacuum gases like argon and nitrogen.

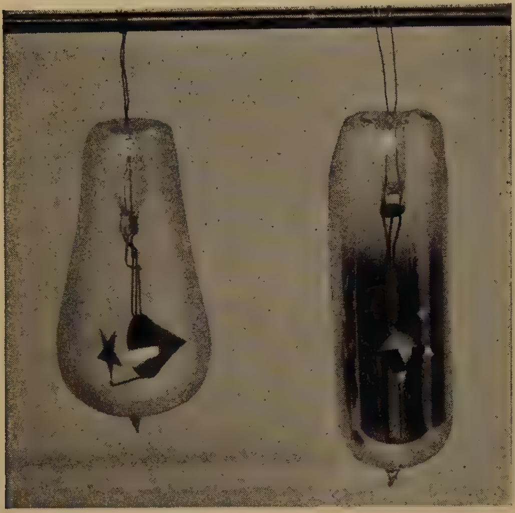


Fig. 1. A Demonstration of the Straight Line Distillation which Takes Place in Good Vacua. In the right-hand bulb, which has inside elements duplicating those in the left-hand bulb, the shadow pattern of the interposing star shows clearly in the film of metal distilled onto the interior wall

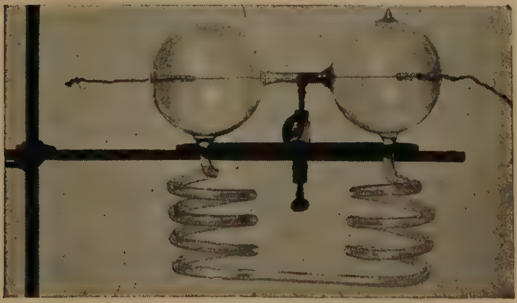


Fig. 2. Hittorf Experiment in which an Electric Current Passed from One Bulb to the Other at Low Gas Pressure Prefers the Longer of the Two Tube Paths

Distillation

When the material of a filament distills in vacuum it does not meet interference to the motion of its molecules, and the distilling substance proceeds in straight lines from the heated source. This is often observed when an incandescent vacuum lamp arcs or burns out. Metal shadows of interior parts of the lamp are then often cast onto the walls. This is shown more clearly when a metal like gold is evaporated from the surface of a tungsten filament in vacuum. By the interposing of a design, as, for instance, the star in the left-hand bulb of Fig. 1, a shadow in gold is cast on the glass as shown on the right-hand bulb of Fig. 1. This simple phenomenon is mentioned because it fits in with the kinetic theory of gases and explains many things observed in vacua. The "mean free path" of molecules or atoms is very long in good vacua, and so straight line distillation occurs.

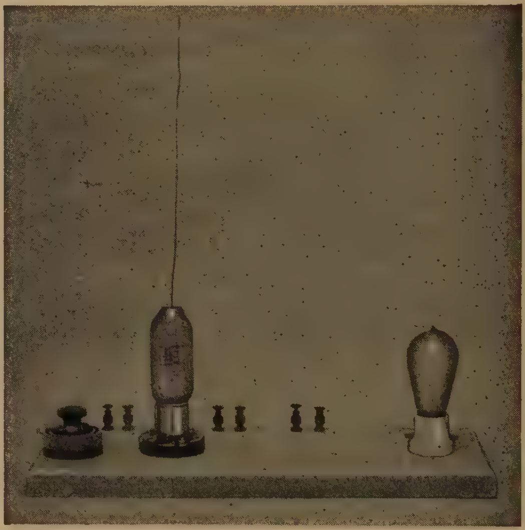


Fig. 3. A Demonstration of the Radiotron Principle. Electron current from the hot filament to the plate of the radiotron tube on the left is made to light the incandescent lamp at the right. This current can be stopped by inducing a negative charge on the vertical antenna wire which is connected to the grid

Hittorf Bulbs

In the historic Hittorf experiment two vacuum bulbs, each carrying an electrode, were joined together by two glass tubes, one very short and one exceedingly long, as shown in Fig. 2. When electric current was passed from one bulb to the other, it evidently chose the longer instead of the shorter path, because the longer tube became highly luminous, while the shorter one did not. This is a quality of electrical conduction in vacua where small quantities of gases still remain, but it cannot be gone into here.

Edison Effect

Another experiment shows the historic Edison effect and its relationship to pure thermionic currents. Where it was once thought that nearly visible particles of the filament were shot across the space between filament legs in vacua, now we recognize, in very high vacua, only the unidirectional motion of negative electrons.

Rectifiers

In vacuum tubes like the kenotron these electrons pass from the hot filament to an electrode commonly called the "plate." This pure emission current is the basis for the so-called rectifiers because only when the filament is negative does any current flow across the space. When gases are present greater currents may be carried, because by the ionization of the gases the moving electrons produce new conductors from the gas molecules. Thus the tungar rectifiers, containing a little argon, and the older mercury vapor rectifiers involve the same principle. Without some gas present the negative electrons, by their very concentration, constitute a space charge which limits the current. This space charge is removed by the ions produced within the gas when present.

Radiotrons

When we interpose a grid or wire screen between the hot filament and the plate of the two-electrode tube or rectifier, we have what we now so commonly use in radio for receiving, for amplifying, and for production of high-frequency currents. The discovery of the controlling or triggering action of the third or intermediate electrode was made by De Forest. A negative charge applied to this electrode or grid interrupts or modifies the electron stream, the current, from the hot filament to the plate. As it takes almost no energy to charge this grid (little more than a "token" of energy, or voltage) the slight power from a radio antenna in its fluctuation may be used to control or to trigger or to let through corresponding jolts of greater energy, which are in turn supplied by some local battery. In the experiment illustrated in Fig. 3, an ordinary incandescent lamp is lighted by current which is passing through a three-electrode tube from hot filament to plate. Its light indicates this current. The grid, or antenna wire, is sticking up from the tube so that it can "pick up" electric charges from space. A small negative charge, produced on a rod of insulating material by merely rubbing it with a piece of paper, causes the lamp to go out or to light up as the charged rod is brought near to or removed from the exposed end of the grid wire.

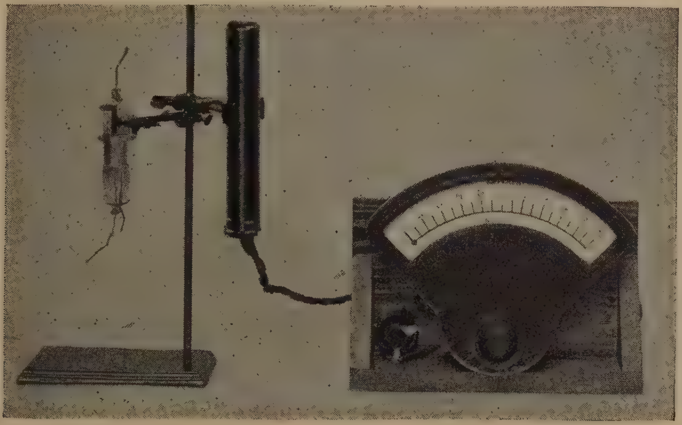


Fig. 4. A Demonstration of the Sensitiveness of a Magnetron Tube to a Magnetic Field. When this two-element tube is suitably arranged, its position with respect to terrestrial magnetism influences the meter reading

Magnetron

As the negatively charged grid cuts off the current of the three-element tube, so an external magnetic field will also do it in the two-element tube, by so influencing or directing the moving electrons that they cannot reach the plate. Such a device is called a magnetron. The particular magnetron used in this experiment, Fig. 4, consisting of a cylindrical plate in a vacuum and a central filament within it, has a coil of wire wound on the outside of the glass. A feeble current sent through the coil from a battery may be made to set up within this coil a magnetic field about equal to that of the earth's magnetic field, so that by moving the whole apparatus about in space (thereby at one time adding to the earth's field, at others opposing it), the magnitude and direction of the earth's magnetic field can be disclosed by a meter which indicates the resultant current. When the magnetron points towards the north pole, the meter shows no current, while in other positions currents are measured.

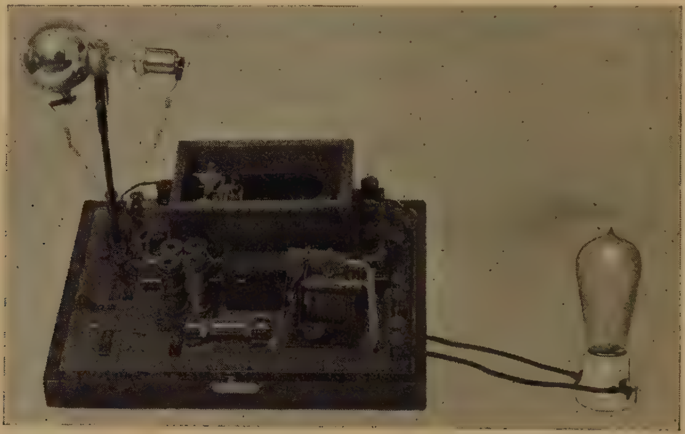


Fig. 5. A Demonstration of the Action of a Photo-electric Cell Connected through a Relay to an Incandescent Lamp. When no light falls on the cell, the lamp burns; when the cell is exposed to light, the lamp is extinguished

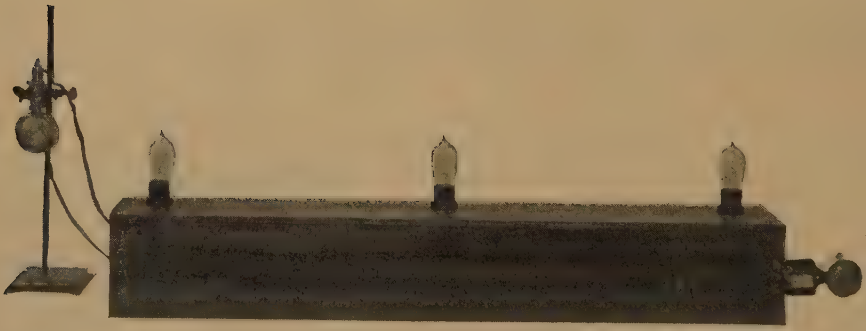


Fig. 6. Apparatus Consisting of a Photo-electric Cell, Indicating Lamps, Capacities and Amplifiers (in box), and a Door Bell Arranged to Demonstrate the Retarded Transmission of an Impulse, such as Nerve Action

Axiotron

Another useful vacuum tube of this type is one in which the magnetic field of the filament current itself becomes great enough during each current cycle to deflect the electrons so that they will not reach the plate. By this tube, "the axiotron," the frequency of an alternating current may be doubled or direct current be changed into alternating.

Photo-electric Cell

Another vacuum tube is the photo-electric cell. As shown in Fig. 5, one of these may be connected with a relay to a lamp so that when light shines upon the cell, the burning electric lamp is extinguished, and relighted on cutting off the light from the photo-electric cell. In other words, it turns on the lamp when it is dark, and turns it off when it is light. This depends on the fact that some metals, like potassium, emit electrons when light falls upon them. These electrons in vacuum constitute a current when they are made to move by the electrical impulse. To repeat; applying potential to a vacuum tube having a potassium electrode and another electrode for leading off the current, causes current to flow in the form of negative electrons from the illuminated metal, and this current actuates the electrical switch which turns off the lighting current of the burning lamp.

The Nerve

This leads to the next, an ambitious physiological experiment. As illustrated in Fig. 6, a photo-electric cell may be made to represent a crude "eye" which is connected to a so-called "nerve" leading to a "brain." The nerve is merely a long box having electrical capacities and suitable amplifiers or three-electrode tubes within. The capacities serve to slow down the apparent rate of flow of the feeble current from the artificial eye so that indicating lamps along the top of the box or "nerve" light up, one after another, as the impulse from the "eye" passes along that path, or the nerve. After the last lamp is thus lighted by these amplified currents an electric bell rings to indicate reception at the "brain" end of the circuit. This is not offered as a reliable replica of the real nervous system, but as an application of the vacuum tube which amplifies the slight energy available and necessary for the experiment. With such slight energy it becomes practicable to show the delayed transmission and reception which is necessary for an illustration of nerve action. Nerve impulses travel much slower than electricity usually does, and this low speed was one objection to visualizing nerves as electrical conductors until Crehore and Williams showed that nerves might be naturally so constructed as to transmit slowly.

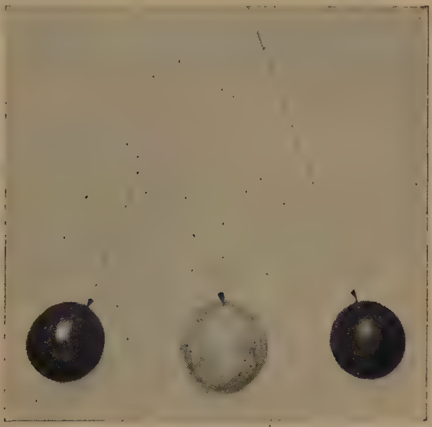


Fig. 7. Three Suspended Rubber Balloons Repelling Each Other to a Triangular Formation as the Result of Being Electrostatically Charged. See Fig. 8

X-ray

In order to show another vacuum product (the X-ray tube) an effect of X-rays may be demonstrated which is not usually thought of in connection with X-rays. Three rubber balloons, suspended close together by long cords, are first charged electrically by friction. They then repel each other and stand stationary in space as at the corners of a large triangle, Fig. 7. As soon, however, as a feeble beam of X-rays is projected towards them in the manner shown in Fig. 8 they quickly discharge and fall to their original position in contact with one another. X-rays ionize air or make it conducting so that the balloons cannot retain their mutually repelling charges. This is the basis of a method for measuring the intensity of beams of X-rays.

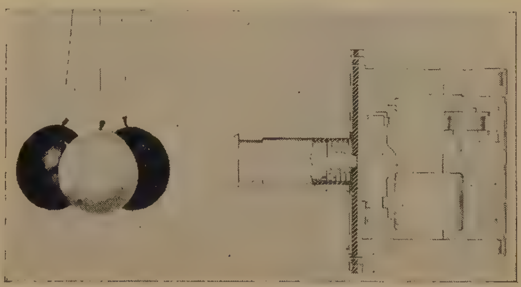


Fig. 8. The Balloons illustrated in Fig. 7 are here shown in their normal positions as the result of their charges having been dissipated by a feeble beam of X-rays

Spectra

Another application of X-rays is in the study of internal structure of crystalline chemical compounds and elements. Cathode rays, currents of negative ions in vacuum, when speeded up by high voltage, produce by their impact X-rays which are characteristic of the material on which they impinge; one may say characteristic of the mass of the atom of the substance of the target. It is through this fact that the X-ray spectra of the elements considered as to wavelengths are arranged in the same order as the atomic masses in the periodic table of Mendelejeff, and by this very method the newest known element, hafnium, has been recently added to the known metals. Referring again to our

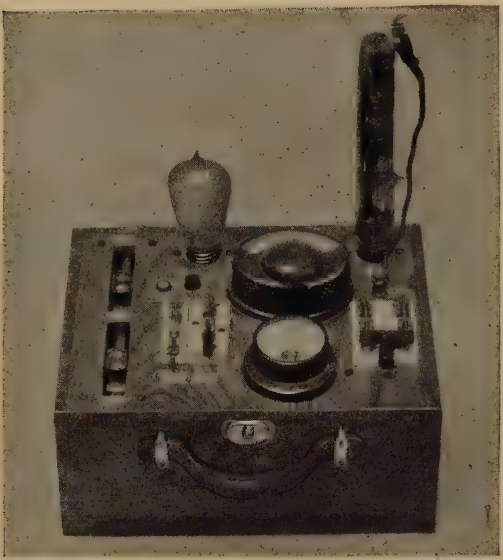


Fig. 9. Apparatus Devised to Demonstrate the Characteristics of Electron Emission from a Thoriated Tungsten Filament

bee analogy, let a fast flying swarm strike bells so hard that they make them ring. From the sound or musical notes we guess roughly the sizes of the bells. We could thus place them in their musical series. The sound corresponds to the X-rays produced when the bees are electrons of cathode rays and sound waves are ether waves. The mass of the bell is disclosed by the tone or frequency; the mass of the atom, by the same sign, is disclosed by the ether wave-frequency. When a certain mineral was used as a surface for the electrons to hit, a new musical note in the ether was found. It was recorded photographically. Its place in the scale of elements had been predicted as accurately as middle *C* on the piano might have been predicted if it had never been heard.

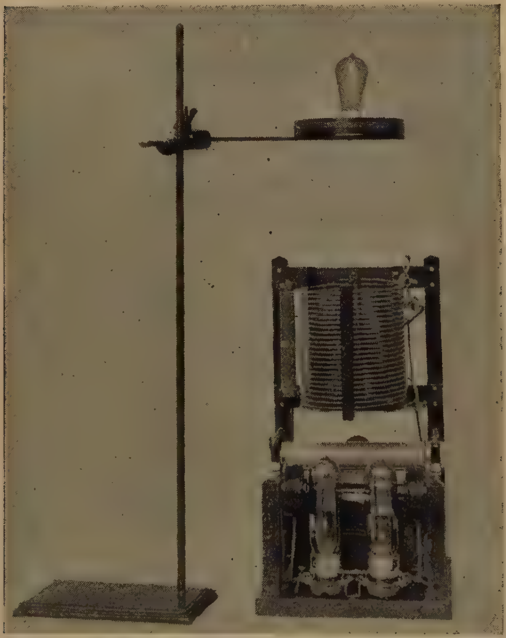


Fig. 10. A Demonstration of the Transmission of Energy Through Space by Means of Waves of Several Million Cycles. The lighted lamp on the stand receives its energy from the source located beneath

With higher voltages the velocity of the cathode rays (or electrons) always increases. In the X-rays thus far produced, however, the penetration or transparency is practically limited to about a quarter of an inch of lead. It is interesting to note that the similar rays from radium, the so-called gamma rays, can penetrate nearly a foot of lead. This corresponds to an exceedingly high electromotive force. Thus radium rays (gamma rays) might be made in vacuum X-ray tubes if millions of volts were applied.

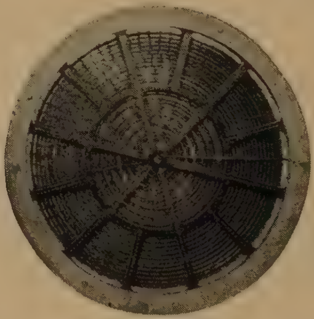


Fig. 11. The Hewlett Loud Speaker. No horn is needed on account of the large size of the diaphragm, 26 in. diameter. The absence of the horn and the distributed exciting coil makes reproduction possible with a high degree of faithfulness. For its operation, a set of vacuum tubes amplifies the microphone current

Atom Layers

The apparatus shown in Fig. 9 (devised by Dr. Hull) is essentially a two-electrode vacuum tube, the tungsten filament having a little thorium in it. At a certain very high temperature this thorium rapidly diffuses to the filament surface. This thorium surface then has the peculiar power of emitting electrons a hundred-thousand times as rapidly as pure tungsten at the same temperature. An ordinary lamp may be lighted in this experiment by letting this thorium electron-emission current flow through the lamp filament. The vacuum tube containing the thorium-coated tungsten also contains a little gas. When the lighted lamp is short circuited for an instant by a switch, the potential on the vacuum tube is thereby greatly increased, and this causes positive ion bombardment of the filament and thus tears the thorium all off the tungsten surface, so that very few electrons are being emitted, that is, those characteristic of pure tungsten at that temperature. Then the load (the lamp) can no longer be carried by the electron current. To repeat, the heavy positively charged gas ions under the impulse of the raised electrical potential act like a powerful sand blast and effectively clean the thorium from the tungsten, thus greatly reducing the emission current. By highly reheating the filament for a few seconds only, a fresh layer of thorium may be diffused to the surface of the filament from within the tungsten, so that then at the previous lower temperature the load or lighting current for the lamp is carried as before by electrons emitted from the thorium surface. This is a proof of the production of a layer of thorium on the tungsten only one atom deep. The electron current from thorium on tungsten is greater than from pure tungsten, and also than pure or massive thorium, and is maximum when the single atom layer is present. This is confirmed by experiments on partial recovery of the surface and supported by thousands of successive repetitions of this experiment on one filament.

High Frequency

By means of an apparatus such as shown in Fig. 10, an ordinary incandescent lamp may be lighted by being brought within a foot of a coil which is carrying a current of several million cycles. This, produced by pulsations, is about as near to wireless transmission of power as anything we now have. This high-frequency principle is also being used by Professor Northrup of Princeton for special electric furnaces. In these, the induced currents in the material of the crucibles or the material to be heated generate high temperature through local resistance.

Loud Speaker

Fig. 11 shows a loud speaker of unusual design. It consists of a 26-in. flat conducting disc, in a magnetic field, the vibrations of which correspond to the voice currents and reproduce the sound waves without the intervention of a horn. To operate this device, vacuum tubes are made use of as follows:

Sound waves entering a microphone cause feeble electromotive forces to be generated in the microphone. These feeble electromotive forces are applied to the grid of a pliotron and cause relatively large variations in the electric current flowing between filament and plate, which in turn are used to secure larger electomotive forces to be applied to the grid of another pliotron. By the use of several amplifying pliotrons the original feeble electric currents are multiplied several thousand times and supplied to the loud speaker which reproduces the original sounds with many times the original volume and great faithfulness of quality. To operate this pliotron amplifier requires a direct current of several hundred volts. This may be obtained by first transforming power from the ordinary alternating-current lighting circuit to a relatively high voltage, next rectifying this high-voltage alternating current by means of kenotrons, and finally smoothing out this pulsating current by means of appropriate electric circuits.

The high degree of faithfulness of reproduction realized in this loud speaker is due partly to the absence of a horn, eliminating horn resonance (one of the usual sources of distortion in a speech reproducer), and partly to the method of vibrating the diaphragm by forces which are distributed fairly uniformly over its surface, instead of acting upon it in a very limited region, as is the case in most other loud speakers. This feature eliminates rattling and ringing of the diaphragm or the production of high overtones by the diaphragm vibrating in its partial nodes.

Direct-current, 3000-volt, Gearless Passenger Locomotive of the C. M. & St. P. Ry. on Exhibition Tour of the East

Featuring electric operation is one of the methods being used by the Chicago, Milwaukee & St. Paul Railway to attract passenger traffic to its transcontinental trains the "Olympian" and "Columbian" running between Chicago and the Pacific North Coast. To reach the largest possible number of persons, the Company is exhibiting one of the 265-ton, 3000-volt, direct-current locomotives at principal cities in the east. The first exhibit was made at Kalamazoo, Mich. From there its itinerary includes Ann Arbor, Detroit, Sandusky, Toledo, Cleveland, Erie, the principal cities between Buffalo and Albany, Newark, Atlantic City, Philadelphia, Harrisburg, Pittsburgh, Columbus, and other points through the middle west, ending up with several days' exhibition at Chicago.

This locomotive is one of five units built by the General Electric Company in 1919 and placed in service in 1920 on the coast divisions of the Chicago, Milwaukee & St. Paul Railway running between Othello, Wash., Seattle, and Tacoma.

When the locomotive was ordered east for this exhibition tour it was coupled to a silk train which it hauled eastward through the 650-mile electric zone. It has since been out of service except for special tests made up to its rated speed of 65 miles per hour at the Erie Works of the General Electric Company on May 19th. These tests were witnessed by a large number of railroad men, who commented on the unusually easy riding characteristics of the locomotive.

The Locomotive on Public Exhibition at Erie, Pa. Its size is indicated by a comparison with that of the standard passenger coach

The number of visitors passing through the locomotive at the various stops averaged from 5000 to 6000, and the largest crowd on record to date was at Cleveland when 11,000 people passed through on the second day. The locomotive is accompanied by a standard day coach such as is used on the transcontinental lines of the Chicago, Milwaukee & St. Paul Railway.

The trip is expected to be finished about the first of August when the locomotive will be immediately returned to service. Mr. L. K. Sillcox, General Superintendent of Motive Power of the Railway Company, has supplied the following figures covering the maintenance of the five gearless locomotives:

Year	Maintenance	Mileage	DOLLARS PER 100 LOCO. MILES	
			Per Loco.	Per 100 T. on Drivers
1921	$66,022.60	304,425	21.69	9.47
1922	60,384.11	294,202	20.53	8.96
1923	62,247.75	278,056	22.39	9.77

Articles describing various features of this locomotive have appeared in the following issues of the REVIEW: Dec., 1919, p. 1004, and April, 1920, pp. 272 and 278.

Detroit Operates New Three-car Articulated Train

By A. C. Colby

Superintendent of Equipment, Department of Street Railways, City of Detroit

Faced with the problem of increasing its carrying capacity 12,000 passengers per hour, to handle rush-hour traffic, the Department of Railways of the City of Detroit made a comprehensive study of the several methods for furnishing this extra service. The comparison of the various additional equipments favored the three-car articulated train proposition. An initial train of this character was accordingly built and placed in regular operation. It will undoubtedly attract widespread attention for it appears to be a decided advance in the means for economically handling dense street railway traffic.—Editor.

The Department of Street Railways, City of Detroit, has recently placed in operation on the Woodward Avenue line a three-car articulated unit designed to handle the heavy passenger traffic on this route. This unit, built by the Cincinnati Car Company and equipped by the General Electric Company, is the first three-car articulated unit placed in service in this country and the first unit of this kind electrically propelled to be placed in operation in the world.

The decision to purchase and operate a trial unit of this type was based on a careful study and investigation of the most economical means of handling the increasing traffic on the Woodward Avenue line.

Nearly two years ago the officials of the Department of Street Railways, realizing that the growth of traffic would require some modifications in the existing rolling stock for the heavier routes, made a careful investigation and study of the rolling stock available for mass transportation. The Woodward Avenue line, which carries nearly 43,000,000 passengers annually and is now operated with motor-car trail-car trains on 60-second headway during rush hours, was selected as typical of the heavier routes in Detroit.

Studies were made on the basis of furnishing off-peak service with motor-car trail-car trains at present and supplementing this service during rush-hour periods with (1) additional motor-car trail-car trains; (2) three-car multiple-unit trains; and (3) three-car articulated trains.

Rush-hour Equipment Compared

Weights and seating capacity of the equipment considered for the rush-hour service are as given in Table I.

It was estimated that the carrying capacity should be increased 12,000 passengers per hour to handle the rush-hour traffic successfully. The comparison shown in Table II was made on the basis of continuing the present off-peak service with motor-car trail-car trains and adding additional service during rush hours to provide an additional carrying capacity of 12,000 passengers per hour, making a total carrying capacity during peak service of 16,200 passengers per hour.

It is evident from the comparison in Table III that the three-car articulated train for the peak service shows lower operating costs, lower first cost and lower total annual charges than the other types of equipment considered. In addition to the advantages of lower weight, lower operating costs, and lower first costs for the articulated unit, it offers the additional advantage of better riding qualities and also lends itself to a reduction in platform labor due to the available passageway between cars.

Articulated Unit Gives Improved Riding

The improved riding obtained with the articulated type of equipment is due to the fact that there is no overhang of the bodies beyond the trucks, adjacent ends of each body being carried on a center bearing on the truck bolster. When entering curves and passing over crossings, the greatest lateral movement on ordinary cars is at the ends overhanging the trucks. In an articulated train of this type there is no overhang at the adjoining car ends. Cars coupled in trains in the ordinary manner are subjected to lateral movement and a tendency to roll from the oscillation transmitted back and forth between the different cars. In the articulated train this does not happen. Although each body is perfectly free to adapt itself to any curve or irregularity in track, there is no tendency to transmit rolling from car to car and in addition there is a dampening action through the side bearings on the connecting vestibules which tends to check any rolling that is set up.

By a study of the general arrangement, it will be seen that the unit is particularly flexible, and lends itself to almost any economical arrangement of platform men which the operating department may deem practical to suit conditions. As loading time is of prime importance with the close headways in Detroit, considerable study was given to the arrangement of seats to allow the utilization of the unpaid entrance area. In analyzing the operating costs in Table III, no consideration was given to a possible reduction in the platform labor by using the articulated unit. It was considered that the platform charges would remain the same for this as well as the multiple-unit train.

Composed of Three Center-door Bodies

The train is composed of three center-entrance center-exit light-weight car bodies mounted on four trucks and arranged for single-end operation. The inside trucks are mounted at the junction and under the vestibule between the first and second, and the second and third car bodies, and are trailer

TABLE I

	Present Motor Car and Single-Deck Trailer	Proposed 3-Car Multiple-Unit Train	Proposed 3-Car Articulated Train
Weight complete train less load, lb	74,000	120,000	75,000
Weight motor car, less load, lb	47,000	40,000	......
Weight motor car, seated load, lb	54,000	47,000	......
Weight trail car, less load, lb	27,000	......	......
Weight trail car, seated load, lb	34,850	......	......
Weight train, loaded (seated) lb	88,850	141,000	94,600
Weight train, loaded (standing) lb	103,400	162,000	114,200
Seating capacity	106	150	140
Pounds per seat	700	800	536

TABLE II

	Motor Car and Single-Deck Trail Car, both Average and Rush	Motor Car and Trail Car in Average Service and 3-Car Mult.-Unit in Rush	Motor Car and Trail Car in Average Service and 3-Car Articulated Train in Rush
Headway, average service, sec	180	180	180
Headway, rush service, sec	47	60	57
Units, required average service	32	32	32
Additional units, rush service	91	64	71
Total units required	123	96	104
Seats, hour in regular service	2100	2100	2100
Carrying Capacity, Rush Service			
Motor-trail-car units	4200	4200	4200
Additional units	12100	12000	12000
Total of line	16300	16200	16200
Annual Car-miles			
Motor trailer	59000	59000	59000
Rush-hour units	22000	22000	22000
Operating Costs, Cents per Car-mile			
Motor trailer	31.2	31.2	31.2
Rush-hour units	31.2	43.8	37.4
Annual Operating Costs per Train			
Motor trailer	$18,400	$18,400	$18,400
Rush-hour units	6,860	9,650	8,228
Total Annual Operating Costs Based on Number of Units Required			
Motor trailer, average service	$590,000	$590,000	$590,000
Rush-hour units	625,000	620,000	584,188
Total	$1,215,000	$1,210,000	$1,174,188

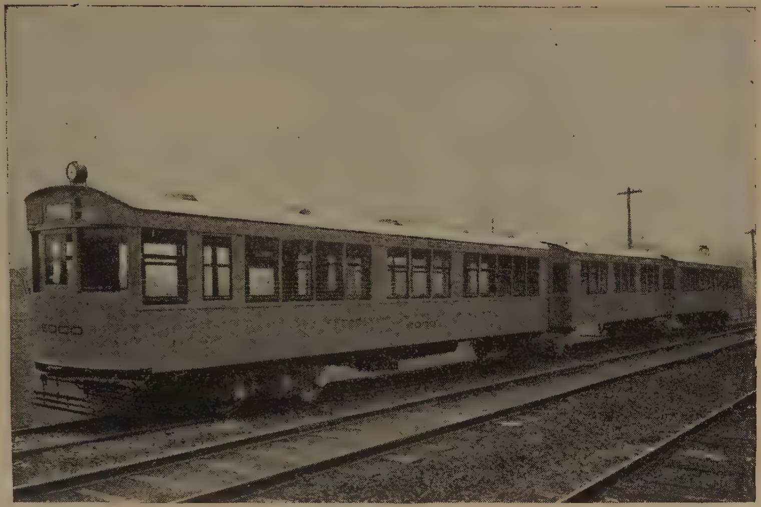


Fig. 1. Three-car Articulated Train Equipped with Four GE-275 60-h.p. Motors and Type K Single-end Control

Fig. 2. Articulated Train in Service in Detroit Shortly After Its Arrival from Cincinnati Under Its Own Power

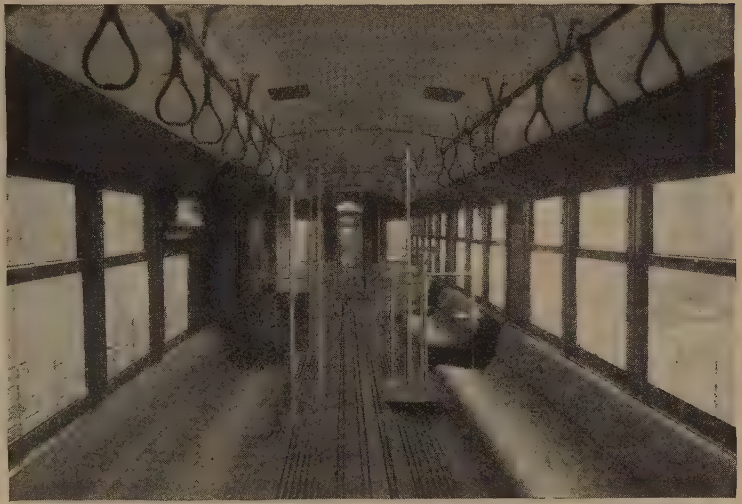


Fig. 3. Interior of Articulated Train Showing Conductor's Position and Arrangement of Seats

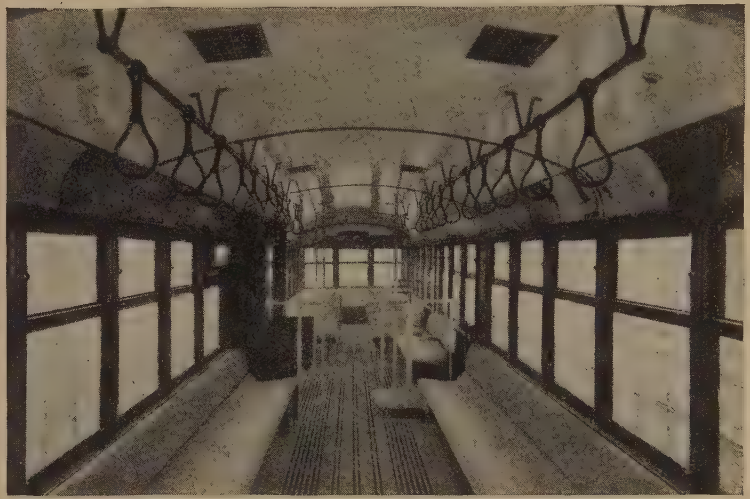


Fig. 4. Interior of Rear Car of Articulated Train Showing Seating Arrangement

TABLE III

	Motor Car and Single-deck Trail Car, both Average and Rush	Motor Car and Trail Car in Average Service and 3-Car Mult.-Unit in Rush	Motor Car and Trail Car in Average Service and 3-Car Articulated Train in Rush
Expenditure for Rush-Hour Units			
91 Motor-trailer trains at $23,000	$2,093,000		
192 Multiple-unit cars at $15,000	....	$2,880,000	
71 Three-car articulated trains at $25,000	....	....	$1,775,000
Fixed charges at 13 per cent	272,000	374,000	231,000
Total annual operating costs and fixed charges	1,487,000	1,584,000	1,405,188

trucks. The two outside trucks mounted under the front end of No. 1 body and the rear end of No. 3 body are motor trucks each equipped with two 60-h.p. motors.

All four trucks are of a special passenger type arch-bar design with large helical springs mounted between the ends of the elliptics and with long helical springs carried in sockets cast on the sides of the journal boxes. They were built by the Cincinnati Car Company and have a wheel-base of 5 ft., 10 in., with 3¾ in. by 7 in. journals. The wheels are 28 in. in diameter and of rolled steel. The trucks are located so that there is a uniform spacing of 34 ft. 1 in. between their centers.

The distribution of load on the four trucks is shown in Table IV. From this tabulation it is noted that 41,960 lb., or 56 per cent of the total light weight, is on the driving wheels. This provides a rate of acceleration with a loaded train of 1.5 m.p.h.p.s. with 16 per cent coefficient of adhesion which is sufficient to insure good acceleration under most any conditions.

The general dimensions of each of the three cars comprising the unit are given in Table V.

Separate Bearing for Each Body

The ends of the center car, and the adjoining ends of the two end cars, are supported on a special type of center bearing on each of the connecting trucks. The 5 in. by 3 in. by ⅜ in. side sill angles are carried around the ends of each of these bodies and extend continuously around the entire body framing except at the side door openings, where they are fastened to the steel box piers which act as vertical compression members to reinforce the framing at the opening. Two pairs of diagonal channels of 3 in., 5–15 lb. material further reinforce the end framing and the entire structure is tied together and stiffened by a No. 12 gauge steel plate, 3 ft. 4½ in. wide.

To the end of this body framing is bolted a substantial steel casting, designed with a projecting nose that is carried directly in a cup in the truck center bearing. The adjoining body ends are each carried in a separate cup. The arrangement has a slight theoretical disadvantage in that the point of bearing is not at the true center of the truck, but this is overcome by allowing a slight additional clearance between the edge of the vestibule and the edge of the body flooring where it is cut out to allow rotation in going around a curve. This design of center bearing avoids carrying one bearing on top of the other and consequently does not require the lower bearing to carry the load of both cars with consequent more rapid wear.

Another feature which was given careful attention in the design is that of lubrication. The parts are retained in place by a horizontal bolt passing through two ears on the lower

TABLE IV

Complete light weight of train, 3 units, 75,000 lb

No. 1 Truck, Front End	
Load on center bearing	11,155 lb
Weight of truck	5,725 lb
Weight of motors	5,000 lb
Load on rail	21,880 lb
No. 2 Truck	
Load on center bearing	11,595 lb
Weight of truck	5,425 lb
Load on rail	17,020 lb

No. 3 Truck	
Load on center bearing	10,595 lb
Weight of truck	5,425 lb
Load on rail	16,020 lb
No. 4 Truck	
Load on center bearing	9,355 lb
Weight of truck	5,725 lb
Weight of motor	5,000 lb
Load on rail	20,080 lb

bearing. This bolt extends between the projecting body noses. When the bolt is in place, a projecting shoulder on each nose prevents it from coming out of the socket and at the same time allows free pivotal motion in any direction. In this way, no bolt holes are required in the sockets and retention of oil is assured. Each body nose casting is cored out to form a chamber for oil and waste packing.

Bottom of Vestibule Forms Side Bearings

The bottom frame of each vestibule is reinforced with a substantial steel ring extending completely around its circumference. This ring is fastened to a built-up side support on the truck bolster by long bolts passing through compression springs above and below, and provided with shims or washers for adjustment. Thus each vestibule is supported entirely on the truck and simply extends into the opening between the posts at the end of each adjoining body. The vestibule floor ring extends above and rests upon the body framing and the body floor is cut out in an arc so that each body is free to rotate on its center bearing while the vestibule remains stationary relative to the truck.

As the body tends to roll from side to side due to track inequalities, a flat steel rub piece on each side of the framing comes in contact with the steel ring under the vestibule and forms a side bearing. The load is transmitted through the vestibule ring to the spring supports on the truck which resist the rolling and tend to dampen it. In effect, therefore, the side bearings in this construction are up against the bottom of the vestibule rather than down against truck supports, as in the usual design.

Clearance is allowed between the vestibule posts in the body and the vestibule itself. These posts are sloped away from the vestibule at the top to allow for rolling. In addition, clearance is allowed between the top of the vestibule and the body header. This is required to take care of vertical breaks in grade. As designed, the train will not only negotiate a 35 ft. radius curve, but also allows clearance for a 10-deg. break in grade at the same time. The openings between the body and the vestibule are enclosed by wood wipers mounted in slides on the end of the body and held against the vestibule by tension springs.

The vestibules are cylindrical in shape and are made of No. 14 gauge sheet steel. They are 54 in. in diameter and 6 ft. 6½ in. high inside, with a steel floor and top plate riveted to the cylindrical shell. The openings for the passageway are cut into the portion of the shell which extends into the car body. These

TABLE V

General Dimensions	Car No. 1	Car No. 2	Car No. 3
Length over all	43′–10½″	33′– 3″	43′–10½″
Length over dash	42′– 8″	31′– 2″	42′– 8″
Length over body	37′– 3″	28′– 0″	37′– 3″
Rail to top of trolley boards	10′–11″	10′–11″	10′–11″
Rail to underside of sill	33″	33″	33″
Extreme width	8′– 2″	8′– 2″	8′– 2″
Width at side sill	7′–11″	7′–11″	7′–11″
Rail to first step	15″	15″	15″
First step to second step	11″	11″	11″
Second step to platform floor	11″	11″	11″
Door openings (center entrance)	30″	30″	30″
Door openings (motorman's door)	30″	30″	30″
Door openings (vestibules between cars)	22″	22″	22″
Diameter of vestibules	4′– 6″	4′– 6″	4′– 6″
Window post centers	30″	30″	30″
Truck centers	34′– 1″	34′– 1″	34′– 1″
Wheel base	5′–10″	5′–10″	5′–10″
Size of wheels	28″	28″	28″
Width of longitudinal seats (side wall over edge of cushion)	25″	25″	25″
Distance between seat cushions	45″	45″	45″
Seating capacity	51	36	53
Total length of train (over buffers)		122′– 8″	
Total seating capacity of train		140	
Radius of shortest curve, inside track		35′	

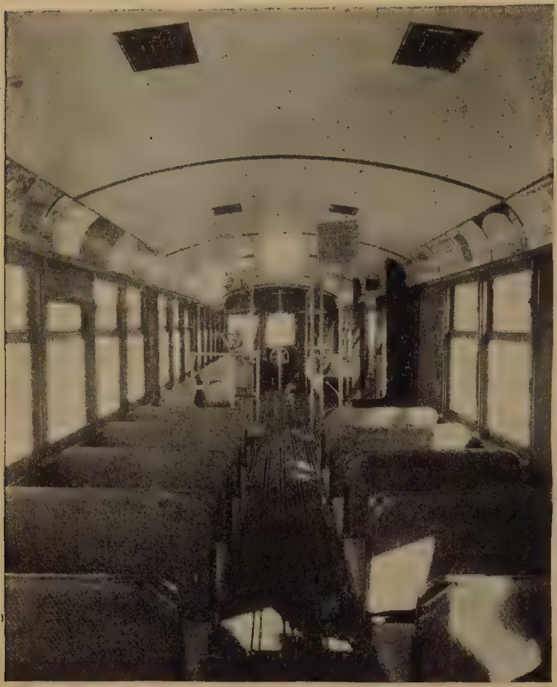


Fig. 5. Interior of First Car of Articulated Train Looking Forward

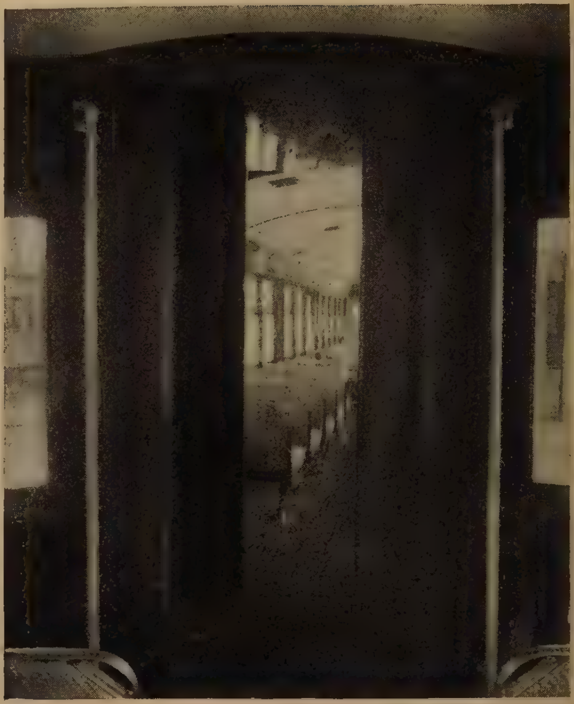


Fig. 6. View of Cylindrical Passage between Cars Showing Position on Curve

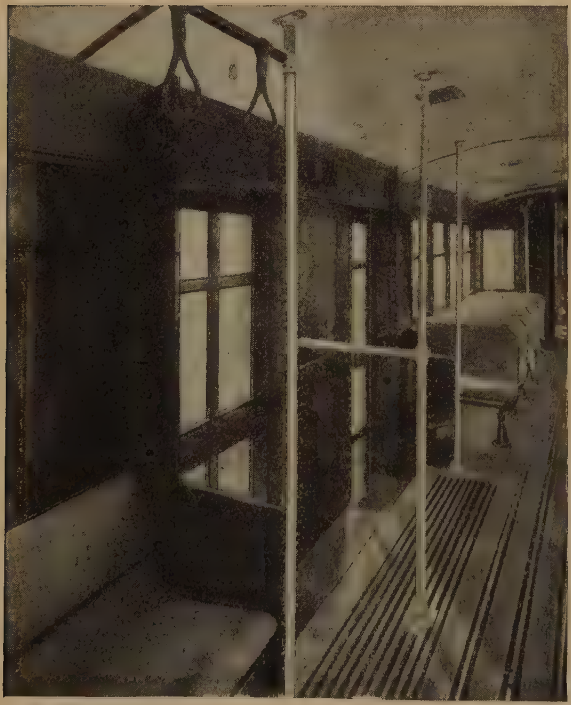


Fig. 7. Interior of Articulated Train Showing Door for Entrance and Exit

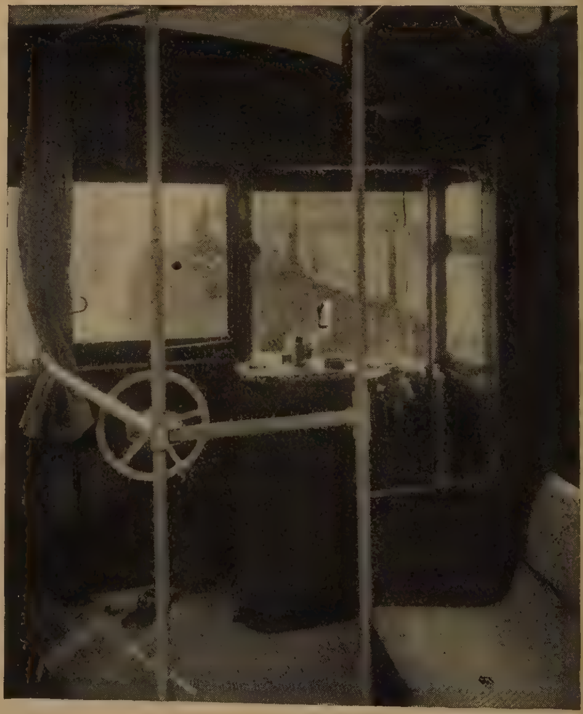


Fig. 8. Motorman's Position Showing Controller and Air Brake Control

openings are 22 in. wide and provide a clear passageway between cars on a track curve of 35 ft. radius.

Careful attention was given to the problem of making the top of the vestibule weatherproof. The steel top is depressed 1 in. and is fitted with a wood disk 1 in. thick with an inverted bevel edge. The disk is made approximately 2 in. smaller in diameter than the steel top so as to form a gutter between the rim of the depressed plate and the wood filler. This gutter collects any rain or moisture which may penetrate under the wiper board above the vestibule. Tubular grab handles extend full length on each side of the vestibule interior and these are connected to the gutter above so as to act as down spouts.

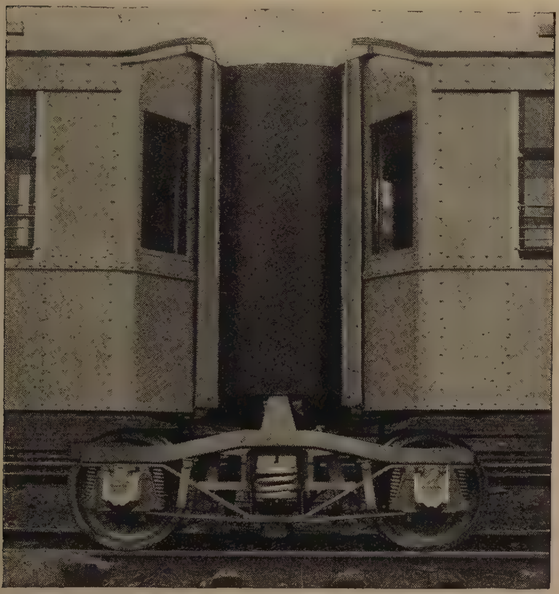


Fig. 9. Connecting Vestibule and Truck Showing Center Bearing and Cylindrical Passageway

A layer of ¾ in. thick cork, covered with linoleum, is applied to the vestibule interior to deaden sound and give heat insulation. This same material is also used in the interior of the body, below the belt rail.

Wood Side Posts Stop at Belt Rail

The side framing of the cars is of the straight plate girder type made of No. 14 gauge sheet steel. The belt rail consists of a formed steel angle covered with a pressed channel which overlaps the outside of the girder sheet. Vertical stiffeners or fins are riveted to the side sheet at each window opening but the ash side posts extend only from the belt rail to the letterboard. These short posts are held in aluminum socket castings by short heat treated bolts that extend through the casting and the belt rail. At the upper end, the posts are bolted through aluminum bracket castings to the wood letterboard. No top plate is used and the pressed U-shaped steel carlines, filled with wood, are supported directly in the bracket castings.

Steel channels of 3 in., 5.15 lb. material extend continuously across the body from side sill to side sill, near each end. Each of these channels is built into a sheet steel box pier at each corner of the body and these piers form the main roof supports. Similar sheet steel box piers are built into the framing adjoining the center door opening.

Aluminum capping pieces on the outside of the side posts hold the upper sash in place. The construction is not continuous, but each sash is made up in an individual window section and set in between the side posts.

Cross sills made of 3 in., 5.15 lb. channel are spaced so as to support the car flooring. These are riveted to the underside of the side sill angles. The framing at the side door openings is reinforced by channels, plates, and angles to form the inside steps to the level car floor.

Cherry is used for the inside trim and is rubbed to a dull natural finish. The headlining is ¼ in. Agasote, curved to the contour of the roof. Railings and stanchions are made of 1 in. aluminum pipe.

In the two side front windows of the leading car, the glass is framed in stationary. The glass in front of the motorman is ⅝ in. thick plate. This is used to assure good vision and also to retard the formation of frost. The center front window is made with a specially designed sash which fits tight against the outside of the posts and is arranged so that it slides sideways outside of and in front of the left-hand window. A two part folding Dutch door is installed at the right-hand corner adjacent to the motorman's position. The upper half is glazed and the lower half paneled solid. The upper and lower halves of the door each fold inwardly and make it convenient for the motorman to make observations along the side of the train without opening the entire door, or to get out to throw switches, etc. Additional knee room for the motorman is obtained by running the air piping from the brake valve inside the dash structure.

Single-end control is used. The brake rigging is installed on the first and last car and is applied to the four trucks just as is done in an ordinary two-car installation. A brake cylinder reservoir and 20 cu. ft. compressor are mounted under the front car and a second brake cylinder and a pair of reservoirs are mounted under the rear car.

One of the standard Detroit five-roll signs has been placed over the front vestibule and one on the side over the door of the center car. This standard sign has proved particularly efficient in conveying sufficient information without the necessity of dash or auxiliary signs.

Table VI lists the principal items of material and equipment as used in the construction of the train.

The operation of this unit will be watched with considerable interest as articulated trains have been given serious consideration by a number of street railways as a means of reducing the weight, first cost, and operating costs of units on lines of very heavy traffic.

The Milwaukee Electric Railway & Light Company rebuilt some of its older type equipments into two-car articulated trains. These have been in operation for a number of years and have been very successful. The Brooklyn Rapid Transit Company recently placed in operation a two-car articulated train made from some of its existing equipment. As both of these installations utilize existing rolling stock, full advantage of articulation could not be obtained. The three-car unit placed in operation by the Department of Street Railways, City of Detroit, is the first unit of its kind in which full advantage of articulation is utilized. The Great Northern Railway of England has operated articulated units in steam service for a number of years with very successful results.

TABLE VI

Motors—GE-275
Air Compressor—CP-127
Signals—Farraday
Control—K-35-JJ
Curtain Fixtures—Curtain Supply Ring 88
Curtain Material—Pantasote Double Fan
Destination Signs—Detroit Special Hunter
Fare Boxes—Cleveland
Fenders—H.B.Lifeguards
Gears and Pinions—G-E Long and Short Add.
Hand Brake—Cincinnati
Heaters—Gold Nickel Chromium Wire
Thermostats—Railway Utility
Headlights—Electric Service H.D.B.
Paint—Pratt & Lambert Enamel
Sand Valve and Traps—Ohio Brass
Seats—Cincinnati Car Rattan Covered
Safety Treads—Kass
Ventilators—Nichols Lintern
Headlining—Agasote

Artist's Drawing of the Three-car Articulated Train in Operation

Studies of Electric Discharges in Gases at Low Pressures

PART I

By DR. IRVING LANGMUIR and HAROLD MOTT-SMITH, JR.
RESEARCH LABORATORY, GENERAL ELECTRIC COMPANY

The relative simplicity of the phenomena in the high vacuum of electron tubes is one of the reasons that these tubes have found such large use. The authors are now engaged in a study of the much more complicated phenomena of gaseous discharges, such as those of the mercury arc rectifier. By new methods of using collecting electrodes, quantitative measurements of many of the fundamental factors of gaseous discharges have been made possible. The theory of plane, cylindrical, and spherical collectors, with retarding and accelerating fields, is presented in the following installment of this series of articles. The next sections will deal with typical experimental data with plane, cylindrical, and spherical collectors, and there will follow a general discussion of these results and their interpretation.—EDITOR.

In a recent number of this magazine[1] it was shown that a great deal of information regarding the nature of the mercury vapor arc could be obtained by studying the volt-ampere characteristics of auxiliary electrodes or collectors placed in the path of the discharge. When the collector is negatively charged, it repels electrons from its neighborhood but gathers positive ions. It thus becomes surrounded by a positive ion sheath or region which contains a positive ion space charge, but no free electrons. The whole drop in potential between the ionized gas and the collector becomes concentrated within this sheath, the positive space charge on the ions in the sheath being able to neutralize the effect of the negative charge on the electrode so that the field of the collector does not extend beyond the outer edge of the sheath. The number of ions taken up by the collector is thus limited by the number that reaches the outer edge of the sheath as a result of their proper motions. The thickness and thus the area of the outside of the sheath can be calculated from space charge equations. The current density over this area measures the positive ion current density in the ionized gas.

In a similar manner it has been found that a positively charged electrode of small size becomes surrounded by an electron sheath, and the current, under these conditions, is limited by the rate at which the electrons reach the edge of the sheath; and in this manner the electron current density in the ionized gas may be measured. Because of the small mass and consequent high mobility of electrons, the electron current densities in uniformly ionized gases are hundreds of times greater than the positive ion current densities. In measuring electron current densities there is a limit to the positive voltage that may be used on the collector, for ionization by collision sets in at a certain voltage and the positive ions produced within the sheath neutralize the electron space charge and allow the current to increase indefinitely without further increase in voltage. Another difficulty is that the electron currents which flow when an electrode is actually positive with respect to the surrounding space are frequently so large that they rob the discharge of available electrons and therefore cause the space potential to rise in proportion to the electrode potential.

If the collector is at a potential slightly negative with respect to the space, electrons may still reach the electrode if they have sufficient velocities to carry them against the retarding field which they encounter within the positive ion sheath. As the collector is made more negative, the lower speed electrons fail to reach the collector, although those with high speed may still reach it. The volt-ampere characteristic of a collector therefore gives indications as to the distribution of velocities among the electrons in the ionized gas.

A very common type of velocity distribution is the random type usually known as the Maxwellian distribution. When the electron velocities have this distribution the current of electrons flowing to any collector at a potential V, which is negative with respect to the surrounding space, is given by the equation

$$i = I A \epsilon^{\frac{Ve}{kT}} \qquad (1)$$

where I is the electron current density in the ionized gas, A is the area of the collector, e is the charge on the electron, k is the Boltzmann constant (1.372×10^{-16} erg per degree), T is the absolute temperature corresponding to the velocity distribution of the electrons, and ϵ the base of the system of natural logarithms. If V is expressed in volts the value of e/k becomes 11,600 (degrees per volt).

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[1] Langmuir, GENERAL ELECTRIC REVIEW *26*, 731 (1923). See also *Science 58*, 290 (1923) and *J. Frank. Inst. 196*, 751 (1923).

COLLECTOR WITH RETARDING FIELD

Equation (1) may be derived as follows: In a state of equilibrium and among particles which have a Maxwellian distribution of velocities, the ratio of the concentrations of the particles in two regions where the potential energies of the particles are different is given by the Boltzmann equation

$$\frac{n'}{n} = \epsilon^{\frac{-E}{kT}} \qquad (2)$$

Here n' and n are the numbers of particles per unit volume in the two regions and E is the work which must be expended in bringing a single particle from the second region (corresponding to n) to the first region.

If we consider that the particles are electrons of charge e (4.774×10^{-10} e.s. units, or 1.592×10^{-19} coulombs) and that the first region has a potential V with respect to the second region, then E, the work needed to move an electron from the second region to the first is $E = -Ve$, so that the Boltzmann equation becomes

$$\frac{n'}{n} = \epsilon^{\frac{Ve}{kT}} \qquad (3)$$

Let us now consider a negatively charged collector surrounded by ionized gas containing n electrons per unit volume moving with Maxwellian velocities corresponding to a temperature T. Let us also assume provisionally that the surface of the collector is a perfect reflector in regard to electron impacts, so that all electrons which strike it rebound elastically, and the current to the collector is zero. Then it is clear that the presence of the collector will not disturb the condition of equilibrium corresponding to the Maxwellian distribution, and the Boltzmann equation can be used to calculate the electron densities within the positive ion sheath enveloping the collector. If V is the potential of the collector with respect to the surrounding ionized gas, then n', the number of electrons per unit volume in an element of space right at the surface of the collector, is given by equation (3). When V is negative the concentration n' of electrons near the collector is small compared to n the concentration in the body of the gas; but the velocity distribution and average energy (temperature) of the electrons, according to well recognized thermodynamic principles, must be the same in both regions. It is true that the electrons which reach the neighborhood of the collector have lost kinetic energy by moving against a retarding field, but these electrons were not average electrons but were those which originally had unusually high velocities.

Consider an imaginary plane in the body of the ionized gas. A certain number of electrons, corresponding to a current density I, pass per second per unit area through this plane from one side to the other and an equal number pass back in the opposite direction. If v is the average velocity of the electrons then we have the relation

$$I = \tfrac{1}{4}\, n\, v\, e \qquad (4)$$

The derivation of this may be readily understood when we consider that $\frac{1}{2} n'$ represents the number of electrons in an element of unit volume which are *approaching* the imaginary plane and that the average *velocity component of these electrons* toward the plane is $\frac{1}{2} v$.

The current density I' of electrons at the surface of the collector is given by an equation like equation (4) and since v is the same for both cases we find

$$\frac{I'}{I} = \frac{n'}{n} \qquad (5)$$

Equation (1) thus gives the current of electrons which strike the surface of the collector under the conditions assumed: Maxwellian distribution and perfectly reflecting collector.

Let us now consider the effect of making the electrode non-reflecting so that it collects all the electrons that strike it. We are then no longer dealing with equilibrium conditions so that any use of the Boltzmann equation requires justification.

If the gas pressure is so low that the free paths of the electrons are large compared to the diameter or width of the collector and if the surface of the collector is convex we can see that equation (1) applies whether or not the surface reflects electrons, for the electrons which strike the collector come without collision from a region so far from the collector that the Maxwellian distribution is not disturbed even if the collector absorbs the electrons. At higher gas pressures and with collectors of large size we may expect to observe deviations from equation (1) particularly when the collector is only slightly negative with respect to the space so that it collects large electron currents.

Taking the natural logarithm of both members of equation (1) we get

$$\log i = \text{const} + \frac{Ve}{kT}. \qquad (6)$$

Thus if we plot the logarithm of the electron current i as a function of the potential V of the collector, we should obtain a straight line of slope $\frac{e}{kT}$.

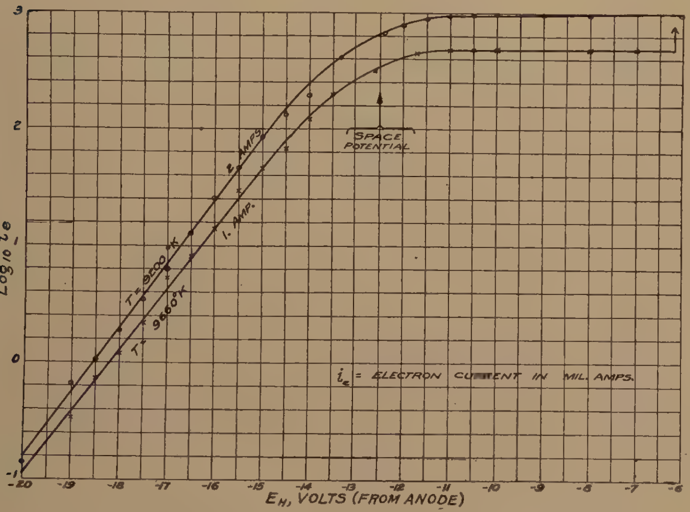

Fig. 1. Semi-logarithmic Plot of Current-voltage Curve for Collector H

For the larger values of the negative voltages applied to the collector, the electron currents become so small that the positive ion currents are no longer negligible compared to them. The current values i to be used in equation (1) or equation (6) are then obtained from the observed currents by subtracting the positive ion currents which flow simultaneously and which can be calculated by methods which will be described later.

Typical experimental data illustrating a straight line semi-logarithmic plot of the volt-ampere characteristic of a collector in ionized gas are given in Fig. 1. The straightness of the lower part of the line proves that there is in this case a Maxwellian distribution of the electron velocities.

COLLECTOR WITH ACCELERATING FIELD

Equation (1) does not apply when the potential of the collector is such as to exert an attractive force on the particles being collected. The Boltzmann equation (3) should apply for *equilibrium conditions* regardless of the polarity of the electrode so that, for a perfectly reflecting electrode, equation (1) would give the current of electrons striking the surface even with an accelerating field. But the increase in current density near the electrode, as compared with that further from it, is then due to the large number of low velocity electrons, resulting from collisions, which are *trapped* within the region around the collector by the accelerating field which prevents their escape. To make this clearer, consider an ionized gas with electrons having velocities corresponding to 11,600 deg. K and let there be in this gas a small collector at a potential of +4 volts with respect to the gas. If the collector were perfectly reflecting, so that no current could flow to it, the electron current density at the surface of the collector would be, according to equation (1), ϵ^4 or 54 times greater than in gas, but the average velocities of the electrons would be the same in both regions. Thus about 98 per cent of the electrons near the filament would have velocities too low to permit them to escape from the accelerating field.

The mechanism by which the low speed trapped electrons accumulate around the collector is as follows: The electrons from the gas when they enter the accelerating field acquire energy corresponding to 4 volts, and this energy is sufficient to enable them to escape again. But if they lose energy by collisions with gas molecules or with each other they cannot escape but remain trapped. Similarly under equilibrium conditions an equal number of the trapped electrons will from time to time gain energy by collisions and thus be enabled to escape.

If now we consider that the collector does not reflect electrons we see that it will gather the previously trapped electrons and will very seriously disturb the equilibrium conditions especially when the pressure is low so that there are relatively few collisions.

The electrons that are collected are then those that have come directly from the body of the ionized gas where the current density is I instead of the 54-fold larger value calculated from equation (1). But the accelerating field causes the paths of the electrons to curve inwards as they approach the collector so that the current collected is greater than AI.

The effect of gas at higher pressures increases the current collected since electrons which lose energy by collision while within the region of the accelerating field are trapped by the field until they finally strike the collector.

In the previous article to which reference has been made,[1] cases were considered where the collector was of large size compared to the sheath thickness. Under these conditions very few electrons or ions can form orbits within the sheath which permit the particle to escape from the sheath again. Thus all the electrons which enter the sheath are collected and the current is

$$i = A_s I \tag{7}$$

where A_s is the area of the outer surface of the sheath.

With low intensities of ionization and small wires as collectors, the diameter of the sheath may be many times greater than that of the collector. The initial velocities of the electrons or ions as they enter the sheath may thus cause them to form orbits which carry them out of the sheath again without colliding with the collector.

The sheath thickness which is involved in these considerations may be calculated by the following space charge equations.

Plane Collector

The ordinary space charge equation involving $V^{3/2}$ is derived on the assumption that the electrons start out from the emitter without initial velocity. The electrons or ions which enter a sheath in ionized gas have a Maxwellian distribution of velocities corresponding to very high temperatures ranging from 10,000 deg. to 50,000 deg. so that these velocities should not be neglected. The proper modification of the space charge equation[2] taking into account the initial velocities is

$$I = \frac{\sqrt{2}}{9\pi} \sqrt{\frac{e}{m}} \frac{V^{3/2}}{x^2} \left(1 + \frac{2.66}{\sqrt{\eta}}\right), \tag{8}$$

where

$$\eta = \frac{Ve}{kT} \tag{9}$$

Expressing I in amperes per cm², V in volts, the sheath thickness x in cm, and substituting the numerical values of e, m and k, the equation becomes

$$I = \frac{2.336 \times 10^{-6}}{\sqrt{m/m_e}} \frac{\nu}{x^2} \tag{10}$$

where

$$\nu = V^{3/2}\left(1 + 0.0247\sqrt{\frac{T}{V}}\right) \tag{11}$$

Here m_e is the mass of the electron and m the mass of the particles collected. Thus when the collector receives an electron current, m/m_e is unity; but when the current is a positive ion current we have

$$m/m_e = 1834\,M \tag{12}$$

where M is the "molecular weight" of the ion (oxygen atom = 16). For mercury vapor $\sqrt{m/m_e}$ is 605, while for argon it is 271, and for helium 85.8.

Cylindrical Collector

Although the effect of the initial velocities of the electrons on the space charge equations for cylinders has not been worked out, we may assume, as a sufficiently close approximation, that the same factor may be used as for plane electrodes. This is especially justifiable as we shall need accurate results from the equation only when the ratio of the diameter of the sheath to that of the collector is not large. We thus obtain

$$i = \frac{2\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{\nu}{r\beta^2} = \frac{14.68 \times 10^{-6}}{\sqrt{m/m_e}} \frac{\nu}{r\beta^2} \tag{13}$$

The quantity β is a function[3] of the ratio of a the radius of the sheath, to r the radius of the collector, which is given by

$$\beta = \gamma - 0.4\gamma^2 + 0.09167\gamma^3 - 0.01424\gamma^4 + 0.00168\gamma^5 - \tag{14}$$

where

$$\gamma = \log_e \frac{r}{a} \tag{15}$$

Spherical Collectors

For many purposes spherical collectors are convenient, particularly where it is desired to have a relatively large collecting surface and avoid the inaccuracies resulting from edge effects on plane electrodes. The space charge equation[4] for this case becomes

$$i = \frac{4\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{\nu}{\alpha^2} \tag{16}$$

Where α is a function of r/a given by

$$\alpha^2 = \gamma^2 - 0.6\gamma^3 + 0.24\gamma^4 - 0.074\gamma^5 + \tag{17}$$

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[2] Langmuir, *Phys. Rev.* *21*, 419 (1923).

[3] A Table of values of β^2 is given by Langmuir and Blodgett, *Phys. Rev.* *22*, 347 (1923).

[4] The derivation of this equation and tables of the function α are being published by Langmuir and Blodgett in the July number of the *Physical Review*, Vol. 24.

When the sheath thickness is small the current of electrons or ions accelerated to a collector is given by equation (7). in which A_s is equal to $2\pi al$ for cylinders and $4\ \pi a^2$ for spheres, l being the length of the cylinder and a the radius of the sheath obtained from β or α in equations (13), (14), (16), and (17).

When the sheath radius is large compared to that of the collector and especially when the initial velocities of the electrons or ions are high the orbital motion of the particles must be considered.

Let the small circle about F in Fig. 2 represent the cross section of a cylindrical or spherical collector charged for example positively with respect to the surrounding space. The field produced by the collector extends only within a region of radius a, indicated in the illustration by the dotted circle. Consider an electron moving with a velocity v_0 along a path AB, and let BC be the extension of the straight line AB. Then the angular momentum of the electron about the filament F is equal to mvp_0 where p_0 is the distance OF from the line AC to the axis or center of the collector.

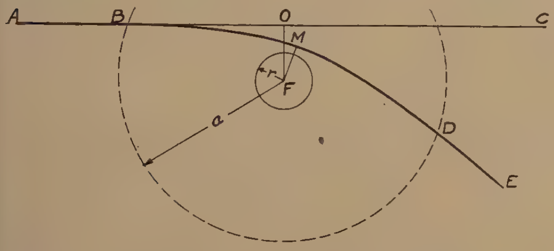

Fig. 2. Diagram of the Path of a Charged Particle Passing Through a Sheath Surrounding a Cylinder or Sphere

The force exerted on the electron by the collector will cause the electron to move along some such path as A B M D E, the portions A B and D E being straight. At some point M the electron will be at a minimum distance p_m from the center of the collector, and at this point the velocity v_m of the electron is wholly tangential. Since the collector can exert only a central force on the electron the angular momentum about F must remain constant throughout the path. Therefore we may place

$$mv_0p_0 = mv_mp_m \tag{18}$$

We shall find it convenient to express the velocities of electrons in terms of the potential differences necessary to produce them. The work done on an electron in moving through a potential difference V is Ve and this is equal to the gain in kinetic energy so that

$$\tfrac{1}{2}\ mv^2 = Ve \tag{19}$$

Combining this equation with (18) we get

$$V_0p_0^2 = V_mp_m^2 \tag{20}$$

where V_0 measures the initial kinetic energy of the electron in volts and V_m is the corresponding energy when at the minimum distance from F. As we now increase the potential on the collector the electron is deflected further so that p_m decreases.

When $p_m = r$, the radius of F, the electron makes a grazing collision with the surface of the collector. If V is the potential of the collector, then the energy of the electron at the moment of collision is measured by $V_0 + V$. Substituting this for V_m in equation (20) and placing $p_m = r$ we obtain

$$p = r\sqrt{1 + \frac{V}{V_0}} \tag{21}$$

In order that any electron may reach the collector the value of p_0 for its path (Fig. 2) must be less than the value of p given by equation (21). In other words p is the radius of the "effective target" of the collector. Thus if I is the current density of the electrons (assumed uniform in all directions) the current taken up by a collector of surface area A for a cylindrical collector is

$$i = AI\sqrt{1 + \frac{V}{V_0}} \tag{22}$$

and for a spherical collector

$$i = AI\left(1 + \frac{V}{V_0}\right) \tag{23}$$

The equations are applicable not only to collectors with accelerating potentials but also to those with retarding potentials. In the latter case V is negative so that i is less than AI and becomes zero when $V = -V_0$, for in that case none of the electrons have energies sufficient to carry them to the collector. Of course the equations are equally applicable to the collection of positive ions.

Although no explicit assumptions have been made in regard to the potential distribution around the collector in the derivation of equations (22) and (23), yet it is clear that there are cases where such distribution can affect the current that flows. For example, with a field of force limited to a sheath of radius a, the current collected by a cylinder of length l certainly cannot exceed

$2\pi a l I$ even though the value of p given by equation (21) may be greater than a. Thus when equations (22) and (23) are applied to collectors having accelerating potentials, the currents given by these equations are to be regarded as upper limits. There are in fact two limits to the current; the current cannot exceed $2\pi a l I$ nor can it exceed $2\pi p l I$. The conditions are much like those that determine the current in an electron tube where the current at a given voltage cannot exceed either the emission from the filament or the current-carrying-capacity of the space as calculated from the space charge equations. Thus with collecting electrodes by altering the conditions we can obtain: (I) currents limited by the *sheath area* or (II) currents limited by *orbital motion*. Just as in the case of electron tubes there is also an intermediate region where both factors are of influence in determining the current. The problem of calculating the current under practical conditions is rendered more difficult by the fact that we do not generally have to deal with electrons which all have the same initial velocity as was assumed in deriving equations (22) and (23) but rather with electrons having velocities distributed by Maxwell's law.

The complete mathematical solution[5] of this problem has been worked out for cylinders and spheres in ionized gases at low pressures.

For retarding fields the solution both for cylinders and spheres becomes identical with equation (1) which we have already deduced more simply from the Boltzmann equation.

THEORY OF COLLECTORS WITH ACCELERATING FIELD

For accelerating fields, the solution for cylinders of surface area A is

$$i = AIf, \tag{24}$$

the function f being given by

$$f = \frac{a}{r} P(\sqrt{\phi}) + \epsilon^{\eta}\left(1 - P(\sqrt{\eta + \phi})\right), \tag{25}$$

where

$$\eta = \frac{Ve}{kT}, \tag{26}$$

$$\phi = \frac{r^2}{a^2 - r^2}\,\eta, \tag{27}$$

and

$$\eta + \phi = \frac{a^2}{a^2 - r^2}\,\eta. \tag{28}$$

Here $P\,(\;)$ stands for the probability integral defined by[6]

$$P\,(x) = \frac{2}{\sqrt{\pi}} \int_0^x \epsilon^{-y^2}\, dy \tag{29}$$

The symbols, V, e, k, T, a and r have the meanings already assigned.

The corresponding solution for spheres is

$$i = AIF \tag{30}$$

the function F being given by

$$F = \frac{a^2}{r^2}\left[1 - \epsilon^{-\phi}\right] \tag{31}$$

Case I: Currents Limited by Sheath Area

With high current density I the sheath thickness becomes small so that with collectors of large diameter $\frac{a}{r}$ does not greatly exceed unity.

When $\eta + \phi > 4$ a very accurate value of f can be obtained from the following equation which is derivable from equation (25).

$$f = \frac{a}{r} P(\sqrt{\phi}) + \frac{\epsilon^{-\phi}}{\sqrt{\pi(\eta + \phi)}}\left[1 - \frac{1}{2(\eta + \phi)^2}\right] \tag{32}$$

If $\phi = 2.0$ the value of f from equation (32) is about $0.95\,\frac{a}{r}$ and for larger values of ϕ it very rapidly approaches the limit

$$f = a/r \tag{33}$$

so that the current is unaffected by orbital motions and can be calculated by the space charge equation (12). A sufficient condition that equation (33) shall hold within five per cent is that $\phi > 2$ and $\eta > 2$.

From equation (27) we see that this condition is equivalent to

$$\eta > 2\,\frac{a^2}{r^2} - 2. \tag{34}$$

In the case of spherical collectors we find by equation (31) that $F = 0.95\,(a^2/r^2)$ when $\phi = 3$, and, for larger values of ϕ, F rapidly approaches the limit

$$F = a^2/r^2 \tag{35}$$

so that the current to the collector is unaffected by orbital effects and may be calculated from the space charge equation (16). The condition, $\phi > 3$, that equation (35) may hold within 5 per cent, is by equation (27) equivalent to

$$\eta > 3\,\frac{a^2}{r^2} - 3. \tag{36}$$

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[5] The derivation of these equations, together with a more complete analysis of the theory of collectors, with consideration of the effects of gases, will be published by the writers, probably in the *Physical Review*.

[6] See Table 24 Smithsonian Physical Tables.

Case II: Currents Limited by Orbital Motion

With low current densities, collectors of small radius, and high initial velocities of the electrons, the sheath radius becomes large compared to that of the collector. For this case we may obtain from equation (25) a more convenient equation by assuming a/r is large compared to unity and expanding the resulting equation as a reciprocal power series which gives

$$f=\frac{2}{\sqrt{\pi}}\sqrt{\eta+1-\frac{2}{3}\frac{\eta^2r^2}{a^2}} \tag{37}$$

This equation gives an excellent approximation to the true values of f whenever $3a^2/(2\eta r^2)$ and η are both large compared to unity. For sufficiently large values of a/r it reduces to the useful expression

$$f=\frac{2}{\sqrt{\pi}}\sqrt{\eta+1} \tag{38}$$

Combining this with equations (24) and (26) and squaring, we have

$$i^2=\frac{4A^2I^2}{\pi}\left(\frac{Ve}{kT}+1\right) \tag{39}$$

Thus if the square of the observed current i is plotted against the potential of the collector a straight line should be obtained. If S is the slope of this line we have

$$S=\frac{4A^2I^2e}{\pi\ kT} \tag{40}$$

or

$$\frac{I}{\sqrt{T}}=\sqrt{\frac{\pi k}{4e}}\frac{\sqrt{S}}{A} \tag{41}$$

$$=0.00822\sqrt{S}/A \text{ amp. cm}^{-2}\text{ deg.}^{-\frac{1}{2}}.$$

The intercept of the straight line on the V axis is obtained from equation (39) by placing $i=0$ and corresponds to a value of V given by

$$V_0=-\frac{kT}{e}=-\frac{T}{11600}\text{ volts.} \tag{42}$$

Thus the straight line represented by equation (39) crosses the V axis at a point $T/11{,}600$ volts negative with respect to the potential of the space around the collector. We shall see that this is an accurate and convenient method for determining the space potentials in ionized gases.

From the slope S we may calculate in a very direct manner the number n of electrons (or ions) per unit volume. The average velocity v of the electrons, given by the kinetic theory, is

$$v=\sqrt{\frac{8kT}{\pi m}}. \tag{43}$$

Substituting this in equation (4) gives

$$n=\sqrt{\frac{2\pi m}{kT}}\frac{I}{e}=4.03\times10^{13}\frac{I}{\sqrt{T}}\sqrt{\frac{m}{m_e}}, \tag{44}$$

and combining with equation (41)

$$n=\frac{\pi}{\sqrt{2e/m}}\frac{\sqrt{S}}{Ae}=3.32\times10^{11}\frac{\sqrt{S}}{A}\sqrt{\frac{m}{m_e}} \tag{45}$$

if $\sqrt{S}$ is expressed in amp. volt$^{-\frac{1}{2}}$.

In a similar way we find for spherical collectors when a/r is large that equation (31) reduces to

$$f=\eta\left(1+\frac{r^2}{a^2}-\frac{r^2}{2}\frac{\eta}{a^2}\right) \tag{46}$$

or if a/r is sufficiently large

$$f=\frac{eV}{kT}=\frac{11600\ V}{T} \tag{47}$$

which gives

$$i=11600\frac{AIV}{T} \tag{48}$$

In this case the intercept of the straight line on the V axis occurs at the space potential.

In the following installment these equations will be applied to experimental data obtained with mercury vapor arcs. The positive ion sheaths around negative collectors are plainly visible in properly constructed apparatus and the thickness of the sheath can be measured accurately. These observed sheath thicknesses will be compared with those calculated by the space charge equations.

(*To be continued*)

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Slip Interference Theory of Hardening

These bibliographies were prepared by Prof. Oscar E. Harder, of the Department of Metallography, Minnesota School of Mines, University of Minnesota, and a few copies were distributed by him in blueprint form. They proved to be most acceptable; a test that indicates the possibility of their usefulness to other persons interested in metallography. Accordingly, we have secured the permission of Prof. Harder to reproduce them for the benefit of our readers.—Editor.

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The Protection of Steam Turbine Disk Wheels From Axial Vibration

PART II

EXPOSITION OF THE NATURE AND THEORY OF VIBRATION IN TURBINE WHEELS

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The first part of this article, which appeared in our June issue, outlined the troubles which gave rise to the investigation and reviewed the preliminary work which led to the discovery of the cause of the difficulty. The second part, which appears below, gives a general discussion of the nature and theory of vibration in turbine wheels and explains why it is necessary to rely on actual tests in addition to purely analytical methods in order to accomplish thorough protection of the factory product. The third and last part will appear in the August number, and will describe the methods of testing and give the procedure which has resulted in the elimination of vibration difficulties from recently built turbines.—EDITOR.

To illustrate standing vibrations in turbine disk wheels, the following method was used. A turbine wheel was mounted in a horizontal position on a stub shaft. An electromagnet was clamped with its poles close to the edge of the wheel. On passing an alternating current through the coils of this magnet a series of pulls was exerted on the wheel tending to deflect it in a direction transverse to the plane of the disk. The frequency of these pulls is twice the frequency of the alternating current used because every complete electric cycle corresponds to two current pulsations in the magnet, and an electromagnet exerts a pull when current flows in either direction through the coil. The alternating-current generator was driven by a variable-speed direct-current motor by means of which the frequency of the magnet pull could be varied over a wide range.

Sand Pictures

Sand was scattered over the wheel surface and the frequency of the magnetic pulls was varied until a particular frequency was reached at which the wheel responded. Fig. 18 shows a case where the wheel vibrated in four segments. In this vibration each segment springs up and down, scattering the sand over to the quiet or nodal zones where there is no up-and-down motion. If, however, the frequency of the deflecting pulls of the magnet is altered even a very small amount, the vibration immediately dies out, although the magnitude of the impulses of the magnet remains the same as before. On raising the frequency of the magnetic pulls another point is found at which the wheel responds. It vibrates in segments, as before, but with six nodal radii or nodes equally spaced around the wheel circumference instead of four.

Figs. 19 and 20 illustrate a 6-node vibration and show that its location is not necessarily dependent on the position of a series of symmetrical discontinuities such as the steam balance holes. Not only does the disk wheel respond when the pull frequency corresponds to four or to six radial nodes, but it may respond readily to frequencies corresponding to 8, 10, 12, or even a larger number of nodes, the number of nodes always being even because for every segment which springs upward during a vibration, the segment next to it on the other side of a nodal line must spring downward. These photographs illustrate the case of a small wheel with short buckets.

Figs. 21, 22, 23 and 24 show cases of 4, 6, 8 and 10 nodal vibrations for the case of a disk wheel carrying long buckets, the total diameter of wheel and buckets being over 8 ft. This wheel was photographed with a layer of paper on the buckets to hold the sand. In the cases of four and six nodes it is seen that the regions of amplitude large enough to move the sand do not extend so deeply into the wheel as in the wheel with short buckets, while in the cases of eight and ten nodes the sand figure is confined to the bucket zone entirely.

The following general observations may be made on this type of vibration in which segments around the edge of the wheel spring up and down, being separated from each other by radial nodal lines:

(1) Every disk wheel responds readily to vibrations of four, six, eight, etc. radial nodes, each type of vibration having its own characteristic frequency.

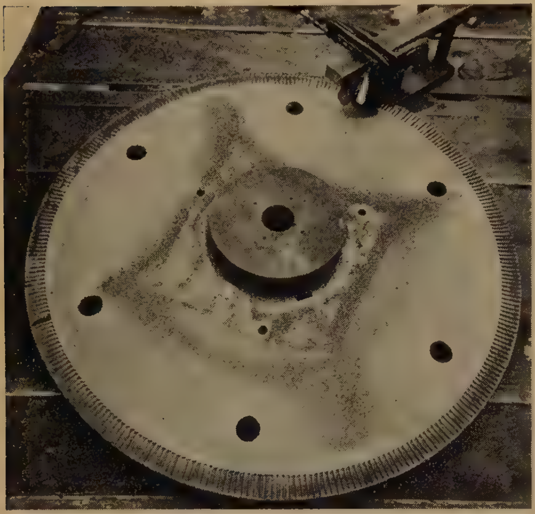

Fig. 18. 4-Node Sand Picture Made by Vibration of a Wheel with Short Buckets

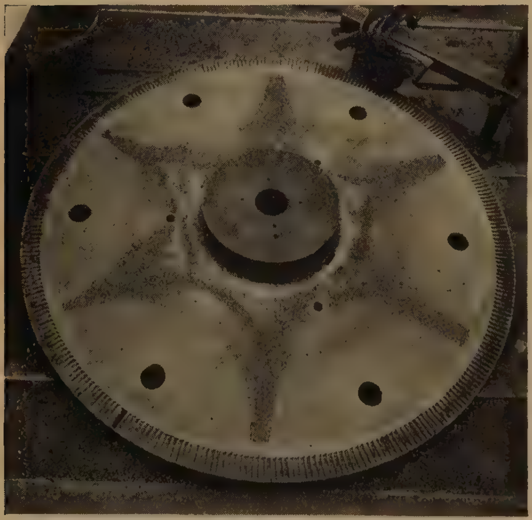

Fig. 20. 6-Node Sand Picture Showing Independence of Pattern from Hole Location. Compare with Fig. 19

(2) The higher the number of nodes the higher the frequency of the vibration and the less easily is the vibration excited.

(3) The higher the number of nodes the more difficult it is to force the sand figures towards the center of the disk.

(4) Both the disk wheel and the buckets vibrate together as a continuous disk and must be treated as a unit in this type of vibration.

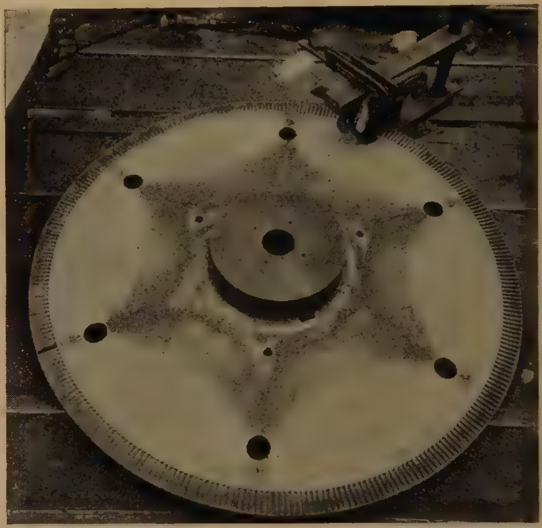

Fig. 19. 6-Node Sand Picture Made by Vibration of a Wheel with Short Buckets

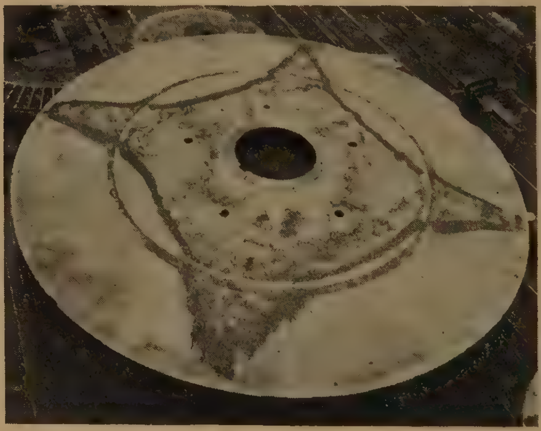

Fig. 21. 4-Node Sand Picture Made by Vibration of a Turbine Wheel with Long Buckets Covered with Paper. The Active Region Extends into the Wheel

Vibrations may also take place with two nodes, as will subsequently be discussed. This type exerts a couple on the shaft transverse to its length, while the types described are balanced in their reaction on the shaft.

Many other types of vibration exist, including concentric ring nodes and combinations of ring and radial nodes. A hybrid form resulting from a combination of six- and twelve-node radial types is shown in Fig. 25. These types of vibration are not readily excited and do not enter into this discussion, because they have not been found to be the cause of serious trouble.

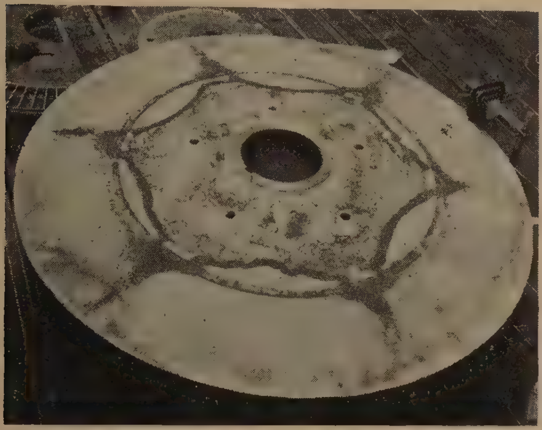

Fig. 22. 6-Node Sand Picture Made by Vibration of a Turbine Wheel with Long Buckets Covered with Paper

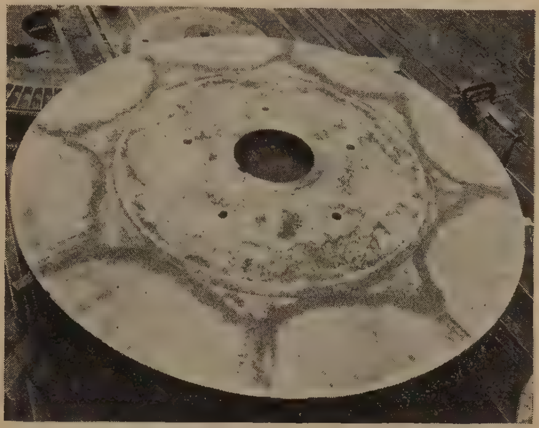

Fig. 23. 8-Node Sand Picture Made by Vibration of a Turbine Wheel with Long Buckets Covered with Paper

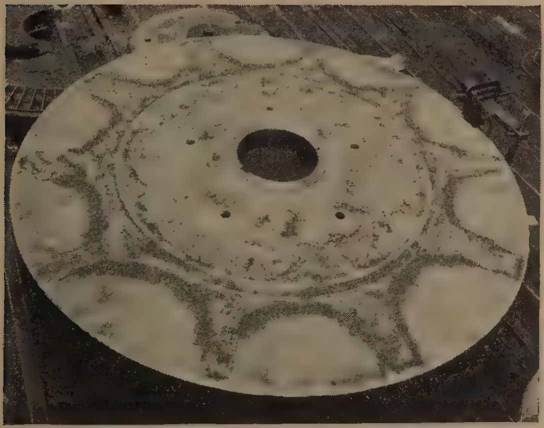

Fig. 24. 10-Node Sand Picture Made by Vibration of a Turbine Wheel with Long Buckets Covered with Paper. The active region is confined to the buckets

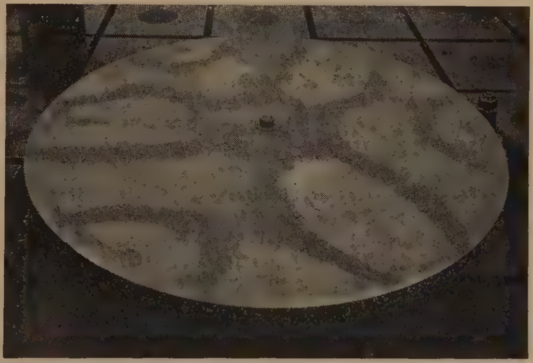

Fig. 25. Complex Sand Picture with 12 Nodes at the Edge and 6 Nodes Near the Center Made by Vibration of a Thin Steel Plate. This is a rare type of motion

Effect of Centrifugal Force on Vibration Frequency

After the natural vibration frequencies of a turbine disk wheel when not rotating are determined as described, a question which arises is the effect upon these vibration frequencies of the rotation of the wheel at high speed. The frequency of a given type of vibration is determined by two factors, (*a*) the stiffness and (*b*) the mass of the vibrating body. The stiffer the body the faster it vibrates, and the more massive it is the slower will it vibrate. Now centrifugal force has no effect on the mass of the wheel, but it has a powerful stiffening effect. This force acting radially outward around the edge of the wheel stiffens it and raises its vibration frequency. This may be compared to the raising of the vibration frequency of a kettle drum by drawing the membrane outward around the edges by the tightening screws. Therefore it may be inferred that centrifugal force raises the natural vibration frequencies of a turbine disk wheel.

It is well known that a particle of mass m with an elastic support, of such stiffness that a force R_s is required to produce unit deflection, will have a natural frequency of vibration, f_s, expressed by

$$f_s = \frac{1}{2\pi}\sqrt{\frac{R_s}{m}} \qquad (1)$$

If the same particle is supported in another manner with an elastic factor R_c, its new frequency will be

$$f_c = \frac{1}{2\pi}\sqrt{\frac{R_c}{m}} \qquad (2)$$

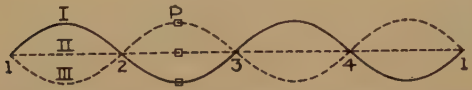

Fig. 26. 4-Node Standing Vibration. The diagram represents the developed edge of the wheel during three successive phases

Now when both stiffnesses act at once the frequency will be

$$f_r = \frac{1}{2\pi}\sqrt{\frac{R_s+R_c}{m}} \qquad (3)$$

Suppose R_s to represent the stiffness furnished by elastic supports and R_c the stiffness contributed by centrifugal effects. Assuming the latter proportional to the square of the speed, N_s, in revolutions per second, this proportionality may be expressed by the use of an arbitrary coefficient B defined by the relation

$$R_c = B\,(4\pi^2\, mN_s^2) \qquad (4)$$

Making use of this relation and eliminating R_s by the use of equation (1) the frequency of the particle, f_r, due to the combined effects of stiffness and rotation may be written

$$f_r = \sqrt{f_s^2 + BN_s^2} \qquad (5)$$

This formula, here derived for the case of a particle, has been justified many hundreds of times for use with a complete turbine bucket wheel by actual measurement as described in later sections of this article. Stodola[1] arrived at the same conclusion on theoretical grounds.

The speed coefficient, B, varies with the design of the wheel and the type of vibration. If the vibrating sectors extend a considerable distance into the wheel so that the deflection curve extends well toward the wheel center, B has a lower value than when most of the bending of the wheel is near its edge, as in the case of a larger number of nodes. The value of the speed coefficient is generally from 2 to 3, and a coefficient as small as unity is rare.

Traveling Waves

Thus far disk-wheel vibrations with radial nodes and the effect of centrifugal force on these vibrations have been discussed in some detail. The type of vibration which has been found to be responsible for serious wheel failures will now be taken up. This type of vibration results when, instead of the wheels vibrating in segments with stationary radial nodes, a wave train travels around the wheel circumference.

Before considering traveling waves, a diagrammatic representation of radial nodal vibrations of a turbine wheel will be presented. Fig. 26 represents diagrammatically the edge of a turbine disk wheel, and shows the curves assumed by it when the wheel is vibrating with four nodes. The drawing shows the edge of the wheel developed as though all points along the entire circumference could be seen at once. Evidently the two ends of each curve correspond to the same point on the wheel and are, therefore, numbered identically.

Curves *I*, *II*, and *III* show three successive stages one-quarter of a complete period apart. The point on the wheel edge marked *P* is chosen half-way between nodal points and vibrates through the maximum amplitude. The points *1*, *2*, *3*, etc., remain stationary as they lie in the quiet nodal radii between the vibrating segments. First the wheel edge is bent as shown by the full curve *I*; one-quarter of a period later the edge becomes straight as shown in curve *II*, but the portions between nodal points have a rapid motion which carries them over to the maximum deflection in the opposite direction in curve *III*, one-quarter of a vibration period later, or one-half a period from the initial position. At the end of a full period, the shape evidently is again the same as it was at the start as indicated by the full line curve *I*. Fig. 27 shows the same sequence for a 6-node vibration.

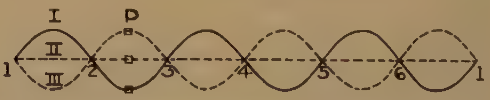

Fig. 27. 6-Node Standing Vibration. The diagram represents the developed edge of the wheel during three successive phases

Fig. 28 shows the developed edge of a wheel in a similar manner and represents the case of 4-node traveling waves instead of standing vibrations. The difference between the case of traveling waves and standing vibrations is seen to be that the nodal points *1*, *2*, *3*, etc., move along the edge of the wheel instead of remaining at fixed points.

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[1] *Schweitzerische Bauzeitung*, May, 1914.

Curve *II* shows the wheel shape after the nodal points *1*, *2*, etc., have moved one-quarter of a wavelength to the right, and curve *III* shows the shape after another one-quarter wavelength motion where the nodes have moved to the right one-half a wavelength in all. At this instant the shape of the wheel is the same as for the case of the standing vibrations previously considered. The difference lies in the motion only. In the case of the standing vibration the nodes are stationary. In the case of the traveling waves the nodes are moving to the right. Fig. 29 shows the same sequence for a six-node vibration.

Comparisons Between Standing Vibrations and Traveling Waves

The following comparisons may be made between the standing vibrations and the corresponding traveling waves for a given disk wheel:

(*a*) In each case there must be an even number of nodes, that is, for every upward portion of the deflection curve there is a corresponding downward portion because of the continuity of the circumference.

(*b*) In standing vibrations the nodes are stationary in the wheel; in traveling waves they move around it. In the first case we have true nodes in the sense that they represent parts of the wheel which are always quiet so they may be observed by the eye. In the second case we have traveling nodes; every part of the wheel edge vibrates and no quiet zones can be seen. A rapidly moving traveling wave can be seen by the eye only by means of instantaneous illumination.

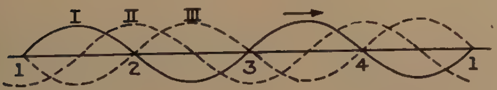

Fig. 28. 4-Node Traveling Wave. The diagram represents the developed edge of the wheel during three successive phases

(*c*) The *frequency* of vibration of every particle along the edge of a given disk wheel is the same *either for a case of standing vibration or for traveling waves*, provided the number of nodes is the same. This important point will presently be explained. A knowledge of it is requisite to the determination of the velocity of a traveling wave from—the standing vibration frequency. For instance, turning to Figs. 26 and 28, it is seen that if the vibration frequencies of each point on the rim are the same in each case, the traveling wave must move to the right one whole wavelength while the standing vibration goes through one complete cycle. Thus *the speed of a traveling wave per second equals the number of complete vibrations of the corresponding standing wave per second multiplied by the length of a complete wave.*

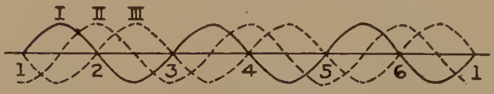

Fig. 29. 6-Node Traveling Wave. The diagram represents the developed edge of the wheel during three successive phases

(*d*) For the standing vibration the *amplitude* of the particles varies along the edge of the disk from zero at the nodal points to the maximum vibration amplitude at points half-way between the nodes. For the traveling waves, all particles around the edge of the wheel vibrate in turn through the same amplitude.

(*e*) For a standing vibration all of the particles along the edge of the wheel vibrate in the same time phase, that is, all particles vibrate together so that each comes to rest at the same instant and each has its maximum velocity of motion at the same instant during the vibratory motion. For traveling waves, however, the particles along the wheel edge do not vibrate in time phase but vibrate one after another in turn, successively coming to rest and successively acquiring their maximum velocity of motion during vibration. Since they all vibrate one after another through the same amplitude a wave shape results of constant amplitude traveling around the wheel edge.

To sum up the last two paragraphs: for a standing vibration, the particles along the edge of a wheel all vibrate in the same time phase, but their amplitudes vary successively between nodes; for a traveling wave all particles vibrate through the same amplitude, but their time phases vary successively along the wheel edge.

Relations Between Standing Vibrations and Traveling Waves

A well-established principle of wave motion is that *standing vibrations with stationary nodes result from the superposition of two identical wave trains traveling in opposite directions, each of which has an amplitude equal to half that of the resulting standing vibration.* A familiar illustration of this principle is observed when two stones are thrown on the surface of a pond giving rise to two outspreading wave trains. Midway between the two stones the two identical wave trains approaching from opposite directions are superposed upon each other. There results in this region a series of standing vibrations of the surface of the pond with stationary nodal points between them. The particles of water vibrate up and down with the same frequency for the standing vibrations as for each of the wave trains of which these vibrations are composed.

This illustration taken from mechanics has other parallels. The sound vibrations in an organ pipe with fixed nodal points are similarly explained by a combination of oppositely moving sound waves. In long-distance electric transmission lines standing vibrations with fixed nodes between them may also be produced by the combination of two oppositely moving wave trains.

A consideration of Fig. 30 will be useful as an illustration. *A*, *B*, *C*, and *D* show successive stages of a standing vibration for each quarter of its period, resulting from the superposition of two identical wave trains moving in opposite directions. The crosses represent the wave progressing toward the right, while the circles show a leftward-moving wave of equal amplitude. When the stage *E* is reached, the cycle is completed and the deflection curve is the same as at the first stage *A*. In the stage *A* the two oppositely moving waves are exactly superposed upon each other so that they add.

When each traveling wave has moved one-quarter of a wavelength as shown in *B* they cancel, so there is zero up or down displacement at all points, resulting in the straight line. After the second quarter of a wavelength of motion both waves are again superposed so that the displacements add, but the displacements are all opposite to those shown in *A*. In stage *D* the deflections cancel again and in stage *E* after each wave train has moved a complete wavelength the deflections add again, giving the original deflection curve.

The important point to be understood is that the natural frequency of vibration of the particles is the same for a standing vibration as for a traveling wave. It has already been explained that the frequency of a particle depends only on its mass and a stiffness factor represented by the restoring force per unit of displacement which, for isochronous vibrations, is the same for each unit of mass throughout the entire structure. The principles of elasticity show that these proportional restoring forces, acting upon the various particles of unit mass, depend on the shape of deformation only. Since the shape is the same for either type of motion, it is seen that the vibration period of each particle is the same in either case.

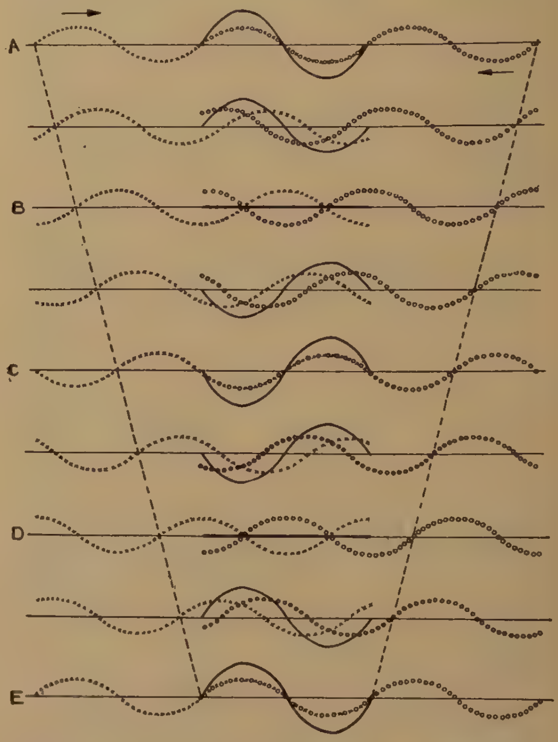

Fig. 30. Composition of Two Equal Waves Traveling in Opposite Directions to Form a Standing Vibration

This explanation shows how the speed of a wave train in a turbine wheel with a particular number of nodes may be calculated from the standing vibration frequency of the wheel when vibrating with the same number of nodes.

Wave Speeds

The point to be emphasized is that a wave train of a particular number of wavelengths travels around the edge of a turbine wheel at *one particular characteristic speed only.* Just as a 4-node standing vibration responds at one frequency so also the 4-node wave trains of which the standing vibration is composed must travel around the wheel at one particular speed. So also for wave trains of 6, 8, or 10 nodes, etc. Each has one particular speed with which it must travel in the disk wheel.

Detection of the Presence of Traveling Waves in a Revolving Disk

Fig. 31 represents the developed edge of a turbine wheel carrying a 4-node wave train, which moves to the right with a certain particular velocity. C_s is a small magnetic coil fixed to the stationary diaphragm so it can register the to-and-fro motions of the wheel in an oscillograph by means of the inductive effect of the wheel as it approaches and recedes from the magnetic coil during vibration. A coil C_r is attached to an arm which is carried around with the revolving disk wheel, so it also can register the vibration frequency of the revolving wheel in an oscillograph.

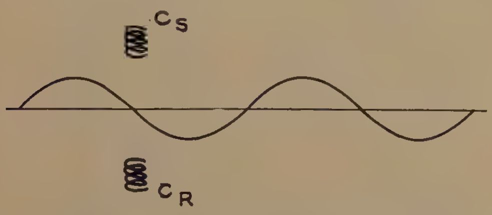

Fig. 31. Developed Edge of a Wheel Carrying a 4-Node Wave

(C_s is a stationary magnetic exploring coil and C_r a similar coil revolving at the same speed as the wheel.)

When the wheel is stationary, both coils register the same frequency. Assume that a wave travels around the wheel 25 times a second. The frequency registered by each coil would be $2 \times 25 = 50$ cycles per second, because for the case of four nodes shown the wheel carries two complete waves.

Assume now that the wheel is revolving at 10 r.p.s. in the direction in which the wave moves. Since the wave always has a definite speed *in the wheel,* the coil carried around *with the wheel* should register almost the same frequency as before. The frequency would be exactly the same were it not for centrifugal force, the effect of which we have already discussed. The wheel is stiffened by it so that the vibration frequencies are raised and the wave speeds are increased. The effect would not be very great at 10 r.p.s. Assume, for example, that the wave train travels around the wheel 26 times a second instead of 25 times due to this cause. The revolving coil will then register $2 \times 26 = 52$ cycles per second when the wheel is revolving 10 r.p.s.

On the other hand, the stationary coil now registers a higher frequency than it registered when the wheel was stationary. The wave train on the wheel is carried forward by the wheel motion at a speed of 10 r.p.s. besides its natural speed in the wheel of 26 r.p.s., so the wave passes the fixed coil at a speed of $10 + 26 = 36$ r.p.s., and the frequency registered by this coil is $2 \times 36 = 72$, because, the wheel carries a train of two waves in the case assumed. Therefore, the forward-traveling wave registers a frequency of 52 cycles per second on the moving coil and 72 cycles per second on the stationary coil; whereas when the wheel was stationary both coils registered 50 cycles per second.

Now consider a case where the 4-node wave train is moving backward in the wheel while the wheel is revolving at the same speed of 10 r.p.s. The effect of the centrifugal force is the same as before so the wave must travel *in the wheel* with the same speed of 26 r.p.s. as before, but in the opposite direction. The frequency recorded by the revolving coil is $2 \times 26 = 52$ cycles per second, the same as for the forward-traveling wave, since this coil records the same frequency for the same wave speed whether the wave moves past it forward or backward. The effect upon the frequency recorded by the stationary coil, however, is different. Since this is a backward-traveling wave, the forward motion of the wheel of 10 r.p.s. allows the wave to travel backward past the fixed coil with a speed of only $26 - 10 = 16$ r.p.s. In other words, the forward motion of the wheel subtracts from the backward motion of the wave as measured by the fixed coil. The frequency registered by the fixed coil is, therefore, $2 \times 16 = 32$ cycles per second for the 4-node backward wave train.

Again, take the case of this disk wheel carrying both wave trains simultaneously and also revolving at 10 r.p.s. For the forward wave train it will be recalled that the revolving coil registers 52 cycles per second and the fixed coil registers 72 cycles per second; while for the backward moving wave train the revolving coil again registers 52 cycles per second and the fixed coil registers 32 cycles per second. The revolving coil registers only one frequency of 52 for either wave train separately or for the combination, but the fixed coil registers 72 for the forward-traveling wave and 32 for the backward-traveling wave, and both 32 and 72 simultaneously for the two waves superposed, that is, for the vibration in the wheel.

To sum up these last two paragraphs, it may be said that when a disk wheel carrying a standing vibration is revolved so that the radial nodal lines are carried around with the wheel, the frequency recorded by a coil carried around with the wheel slowly rises due to centrifugal force as the speed of the wheel increases. The frequency recorded by a coil fixed on the diaphragm, so that it does not revolve with the wheel, registers two frequencies, the higher frequency due to the forward-moving component wave train and the lower frequency of the backward-moving component wave train. These two frequencies diverge more and more as the wheel speed is increased.

Frequency-Speed Diagram

These facts are shown graphically in Fig. 32 which gives a diagrammatic representation that has been found to be very useful.

The vertical scale represents the frequency registered in an oscillograph by the magnetic coils, and the horizontal scale the rotational speed of the disk. The middle curve gives the variation of frequency with speed as recorded by the revolving coil. The upper and lower curves show the two frequencies registered by the fixed coil, the upper giving the frequency due to the forward component wave and the lower the frequency due to the backward component wave train of the 4-node vibration. When the wheel is at rest the figure shows that both coils register 50. As the speed of the wheel is raised to 10 r.p.s. the revolving-coil frequency rises to 52 and the two frequencies recorded by the fixed coil diverge, the upper rising to 72 and the lower falling to 32.

The gradual rise of frequency of the wheel as its speed is increased is expressed by equation (5) previously derived.

$$f_r = \sqrt{f_s^2 + BN_s^2}$$

The upper curve shows how the frequency of a forward-moving wave train, as measured at a fixed point, rises relatively to the frequency detected by the revolving coil, because this wave train is carried forward by the wheel, and is thus passing the fixed coil at a higher speed than it would were the wheel not rotating. This rise in frequency is measured by the number of wavelengths per second that the wave train is carried forward by the wheel rotation which equals the product of the number of waves on the wheel rim, $\frac{1}{2}n$, by the number of revolutions per second of the wheel, N_s. This product $\frac{1}{2}nN_s$ is the frequency in excess of that of the wheel as measured by the revolving coil, that is, in excess of f_r. If H is the higher frequency recorded by the stationary coil and represented by the upper curve, then

$$H = f_r + \tfrac{1}{2}nN_s \qquad (6)$$

In the same way the lower curve shows how the frequency of the backward-traveling wave as measured at a fixed point is decreased because in this case the wave motion is opposite in direction to the motion of the wheel.

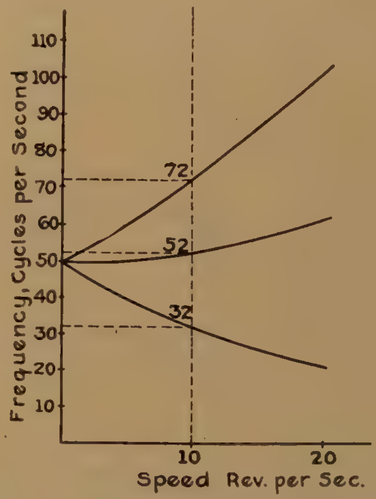

Fig. 32. Frequency-Speed Diagram for 4 Nodes

Thus if M is the lower frequency recorded by the stationary coil and represented by the lower curve,

$$M = f_r - \tfrac{1}{2}nN_s \qquad (7)$$

If the backward-moving component wave train is absent, only the upper frequency is registered by the fixed coil corresponding to a forward-moving traveling wave. If the forward-moving component wave train is absent, only the lower frequency is recorded due to the backward-traveling wave. The frequency recorded by the revolving coil, however, is always the same whether one or both of the component wave trains exist and in whatever relative amplitudes they exist.

It is therefore evident that by the use of two exploring coils as described, one revolving with the wheel and the other being fixed in space, the presence of a forward- or a backward-traveling wave train or both can be detected.

The first observation of traveling waves in a turbine wheel was made by means of fixed oscillograph coils installed in the diaphragms of an operating turbine in 1919. Early in 1920 during the investigation of another turbine, several stages were equipped with two such coils 30 deg. apart. One of these stages yielded the records reproduced in Fig. 33.

Observation of Traveling Waves by Means of Two Fixed Coils 30 Deg. Apart

The upper curve of Fig. 33 is produced by the 25-cycle alternating-current generator being driven by this turbine. Since the generator has two poles, it revolves once for every cycle, and this alternating-current frequency curve marks off the generator revolutions on the film. The two lower oscillograph curves are the records of the two fixed coils, 30 deg. apart. Time is measured to the right. The upper of these two curves is the record of the first of the two fixed coils. The lower curve is the record of the second coil, set in the diaphragm 30 deg. beyond the former so a given point on the disk wheel reaches this coil somewhat later than the first one.

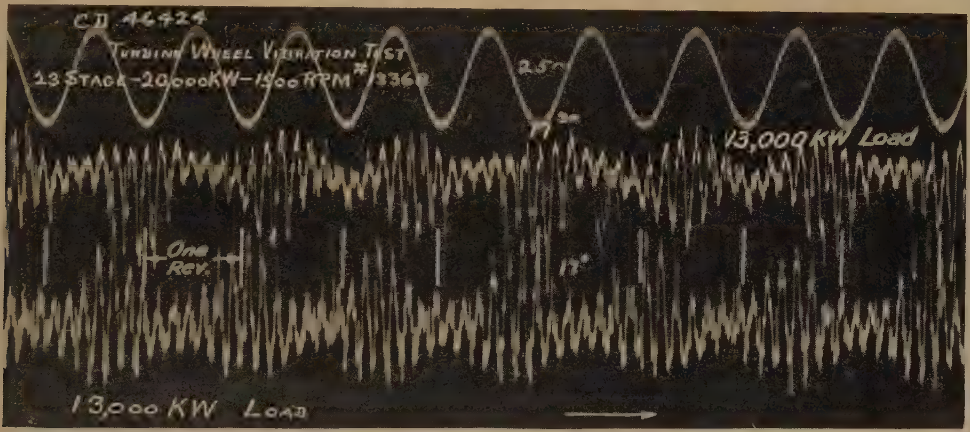

Fig. 33. Oscillograph Records Made by 17th Stage of 20,000-kw., 1500-r.p.m. 23-Stage Turbine

(The upper curve is a 25-cycle timing wave. The other two curves were made by stationary coils 30 deg. apart. This is a case of 6-node forward- and backward-traveling waves.)

The records of these two coils show a close correspondence, both having a high-frequency oscillation which goes through a low-frequency pulsation in amplitude giving the effect of beats. Furthermore, the upper curve lies behind the lower one by about one-quarter of the distance between the low-frequency amplitude pulsations or beats. Since the time recorded by the amplitude pulsations is four times as great as that by which the upper record lies behind the lower, due to the 30 deg. between the coils, the most likely explanation is that there are high spots on the wheel, 4×30 deg., or 120 deg., apart, which cause this amplitude pulsation. This can be made clear from a consideration of Fig. 34.

The wheel revolves in a counterclockwise direction as shown by the arrow. The two coils marked *1* and *2* are 30 deg. apart, and are fixed in space. The diagrammatic oscillograph record shows the beats recorded by the two coils, No. *1* lagging behind No. *2* by one-quarter of a period. Since it takes four times as much time for successive high spots to reach a given coil as for a given high spot to pass from one coil to the other, these high spots must be 4×30 deg., or 120 deg., apart on the revolving disk. The inference is that these high spots are wave crests corresponding to a train of three waves, 120 deg. apart, and that the waves cause the disk wheel to approach and recede from the recording coils periodically. When the wheel is close to a coil, the oscillograph responds strongly, and when it recedes the oscillograph responds less strongly.

If there is such a wave train the question now is to determine its direction and speed. The high spots evidently move in a clockwise direction opposite to the wheel rotation, because they reach coil No. *2* before they reach coil No. *1*, as shown in Fig. 33 where the record of coil No. *2* shows a time lead over that of coil No. *1*. This means that the wave which causes these low period pulsations is traveling in the wheel against the direction of wheel rotation, and that this wave train travels backward even faster than the forward rotational speed of the disk wheel. Therefore, to find the backward speed of this wave train in the wheel it is necessary to add the speed with which it travels backward past the fixed coils to the forward rotational speed of the wheel. From Fig. 33 it is seen that 6½ high spots pass a given coil for nine revolutions of the wheel, or since the wheel revolves 25 times per second, 6 1/2×25/9=18 1/18 high spots per second. Since there are three wavelengths on the wheel corresponding to the three high spots 120 deg. apart, 18 1/18 high spots per second corresponds to a wave speed past the coils of 18 1/18÷3=6 1/54 r.p.s. The wheel revolves forward 25 r.p.s. so the wave speed in the wheel=25+6 1/54=31 1/54 r.p.s.

The conclusion is thus reached that this wheel carries a train of three waves 120 deg. apart (corresponding to 6 nodes) and that this wave train moves backward in the wheel 31 1/54 r.p.s. which is 6 1/54 r.p.s. faster than the wheel revolves forward, so the wave passes the fixed coils 6 1/54 r.p.s. in a backward direction.

Thus far there has been no attempt to explain the cause of the superposed higher frequency which shows strongly in the record of Fig. 33. This higher frequency is found to have 60 1/2 periods while the wheel revolves 9 times, or a frequency of 60 1/2×25/9=168 1/18 cycles per second as measured on the fixed coils, since the disk wheel revolves 25 times a second. This frequency is due to a forward-moving wave train of exactly the same type as the backward-moving wave train, that is, a train of three waves 120 deg. apart, or a 6-node wave train. If such a wave train registers a frequency of 168 1/18 cycles per second on the fixed coils, its speed past these coils must be 168 1/18÷3=56 1/54 r.p.s., because there are three wavelengths on the wheel rim. Since this wave train is assumed to move forward and the wheel is also moving forward, its speed *in the wheel* must be less than that registered by the fixed coil by an amount equal to the wheel speed, that is, 25 r.p.s., because the wave train is carried forward by the wheel rotation. This gives a wave speed in the wheel of 31 1/54 r.p.s. But this is exactly the characteristic speed of a train of three waves as it checks with the speed of the backward-traveling wave train of this type already found. It will be recalled (from the first paragraph under the heading "Wave Speeds") that a given type of wave has a definite speed in a disk wheel which revolves at a given speed, and that this wave speed is the same whether the wave train travels forward or backward in the wheel. This coincidence is therefore striking evidence of the truth of the statement that the high frequency registered was caused by a forward-moving wave train of six nodes, that is, of the same type as the backward-moving wave train.

There is further evidence that the wave train recording the higher frequency is moving forward and the wave crests are 120 deg. apart as in the case of the backward waves.

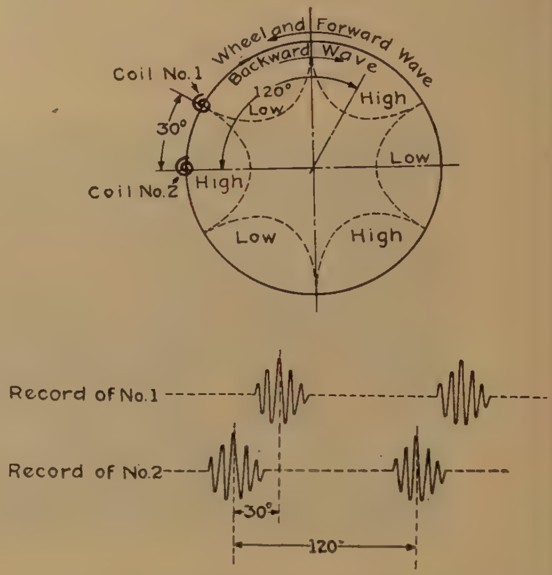

Fig. 34. Diagram Showing 6-Node Forward and Backward Waves Such as are Recorded in Fig. 33

From a close examination of the film record of Fig. 33 it will be seen that the higher frequency of coil No. *1* leads that of the lower record by a fraction of a period. (The polarity of the two coils happens to be opposite in this record.) This means that the disturbance producing this harmonic moves *forward* because it reaches coil No. *1* before it reaches coil No. *2*. Furthermore this lead is as before about one-quarter of a complete period. This again corresponds to waves which are 4×30 deg., or 120 deg., apart.

As to the relative amplitudes of these two wave trains, a casual inspection of the film shown in Fig. 33 might lead one to believe that the amplitude of the forward wave train producing the higher frequency was as great as that of the backward wave train. It is necessary to keep in mind, however, that in an oscillograph record the amplitude is dependent on the induced voltage which in turn depends on both the amplitude and the frequency of the vibration so that higher frequencies have amplitudes recorded which are magnified in proportion to the increase of frequency. For instance, since the higher frequency is about nine times as great as the lower in Fig. 33, the higher frequency would be expected to be amplified about nine times as much as it should be compared with the lower frequency recorded. In all probability the amplitude of the backward-traveling wave is greater than that of the forward wave. There are other reasons for believing this, to be considered later.

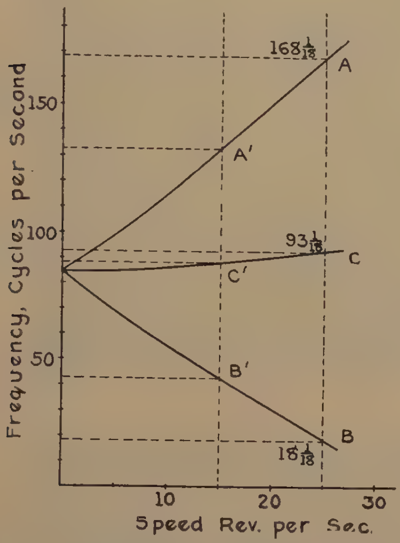

Fig. 35. Frequency-Speed Diagram for 6 Nodes. Points *A*, *B* and *C* were determined from the record in Fig. 33

The film record in Fig. 33 which has just been analyzed is the one which is reproduced on page 916 of the fifth edition of Stodola's book on Steam and Gas Turbines.

Fig. 35 shows the frequency speed diagram for this wheel for six nodes. *A* and *B* correspond to the high and low frequencies recorded by the film shown in Fig. 33, that is, 168 1/18 and 18 1/18 cycles per second or to the wave speeds 56 1/54 and 6 1/54 r.p.s., because in the case of six nodes the wheel carries three complete waves. *C* equals the value of f_r, the frequency of the wheel itself rotating at the normal running speed of 25 r.p.s. This may be calculated by formulas derived from equations (6) and (7).

$$f_r = H - \tfrac{1}{2}nN_s \qquad (8)$$

$$f_r = M + \tfrac{1}{2}nN_s \qquad (9)$$

Thus $f_r = 168\,1/18 - 75 = 93\,1/18$

$f_r = 18\,1/18 + 75 = 93\,1/18$

Suppose the 6-node wave train should still persist with the speed of the disk wheel whose 6-node characteristics are shown in Fig. 35 reduced from 25 r.p.s. to 15 r.p.s. Then the fixed coil would record the frequencies *A′* and *B′* instead of *A* and *B*. If there were a revolving coil, it would record the frequency *C′* instead of *C*. If the wheel were brought to rest with the wave still persisting, both coils would record the same frequency or the standing frequency *E* for six nodes. It can therefore be seen that if the standing frequency *E* is measured for a given number of nodes such a diagram can be constructed to a fair approximation, because an approximate value of the speed coefficient can be assumed. For dependable results, however, rotational tests are necessary with the wheel-testing machine which will be described in Part III of this series. The frequency-speed diagram may have on it curves for all of the usual types of radial nodal vibrations as, for instance, 4, 6, 8, and 10 nodes.

Fig. 33, the record just discussed, is the record of the 17th stage of a 23-stage, 20,000-kw. turbine. This record was taken while the machine was carrying 13,000-kw. load. Fig. 36 shows a record of the same wheel, but with only 5000-kw. load. No vibration phenomena developed at this load. The jagged and irregular record repeats exactly for each revolution. It may be regarded as the wheel autograph, and due to slight irregularities in the rim opposite which the coils are placed. These are magnified because of the high speed. Fig. 37 shows where the load has been raised to 9000 kw. Not until the load reaches 11,000 kw. as shown in Fig. 38 do the vibration phenomena distinctly develop. Fig. 39 shows the record at a 20,000-kw. load or full load. The wave phenomena when once developed appear to remain about the same up to 20,000-kw. load.

Observation of Traveling Waves by Means of Two Fixed Coils 90 Deg. Apart

Fig. 40 gives the frequency-speed diagram for the 17th stage of a 23-stage, 1800-r.p.m., 15,000-kw. turbine, where wave motion in a wheel was detected by means of two fixed

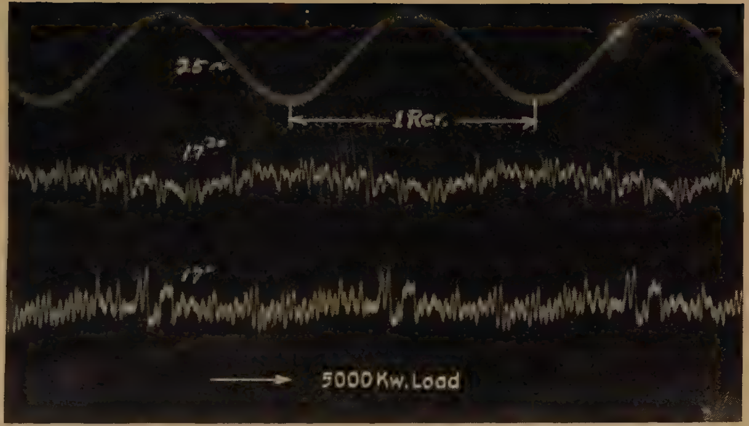

Fig. 36. Oscillograph Records Made by 17th Stage of 20,000-kw., 1500-r.p.m., 23-Stage Turbine, 5000-kw. Load. This is the "autograph" of a smoothly running wheel

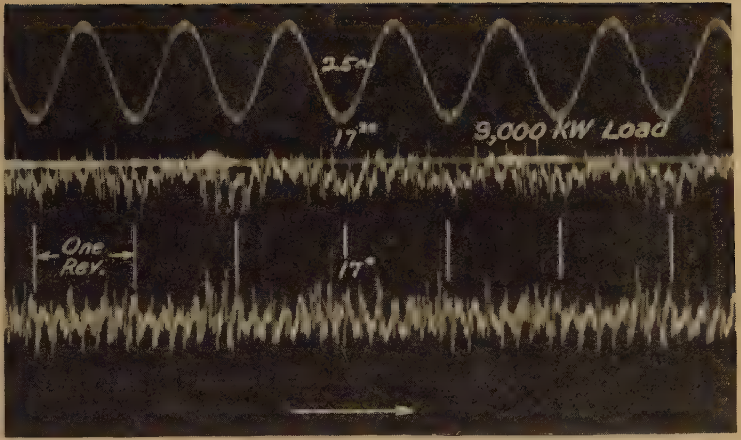

Fig. 37. Oscillograph Records Made by 17th Stage of 20,000-kw., 1500-r.p.m. 23-Stage Turbine, 9000-kw. Load. Wave motion has not yet developed

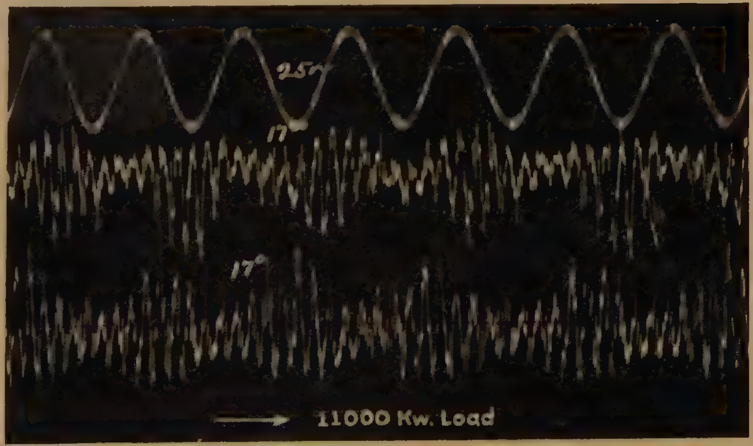

Fig. 38. Oscillograph Records Made by 17th Stage of 20,000-kw., 1500-r.p.m., 23-Stage Turbine, 11,000-kw. Load. Wave motion is fully developed. Compare with Fig. 33

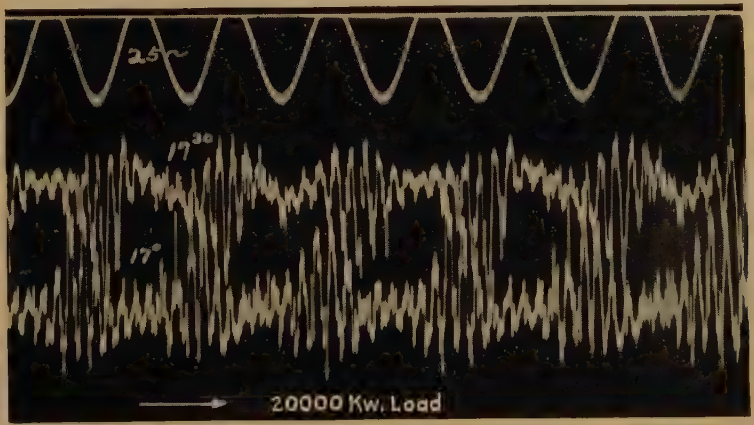

Fig. 39. Oscillograph Records Made by 17th Stage of 20,000-kw., 1500-r.p.m., 23-Stage Turbine, 20,000-kw. Load. Wave motion still maintained

coils on the diaphragm. In this case the coils were 90 deg. apart. Fig. 41 shows the record from which the diagram was made. This case differs from the one previously described in that the higher frequency recorded due to the forward-moving wave develops only after the load is removed. The removal of load is shown by the upper curve which registers the electrical frequency of the generator becoming a straight line, remembering that time is measured to the right. The higher frequency develops in about one second of time, corresponding to 60 alternating-current cycles of the upper curve. As this is a 4-pole machine two alternating-current cycles correspond to one revolution, and 30 r.p.s. is the running speed of the machine.

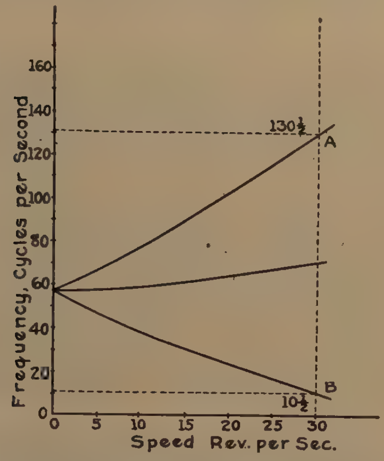

Fig. 40. Frequency-Speed Diagram for 4 Nodes. 17th Stage of 15,000-kw., 1800-r.p.m., 23-Stage Turbine

(Points *A* and *B* were determined from the record in Fig. 41.)

This is known to be a case of four nodes or of two waves 180 deg. apart, because from the record it appears that it takes half as long for a high spot to go from one coil to another as for two successive high spots to pass one coil. The high spots are twice as far apart as the coils, that is, 2×90 deg. = 180 deg.

Another good check is obtained by the use of equations (6) and (7) derived in connection with the frequency-speed diagram.

$$H = f_r + \tfrac{1}{2} n N_s$$

$$M = f_r - \tfrac{1}{2} n N_s$$

Subtracting,

$$H - M = nN_s, \text{ or } n = \frac{H-M}{N_s} \qquad (10)$$

From the frequency-speed diagram shown in Fig. 35 corresponding to the film in Fig. 33 previously discussed, $H = 168\ 1/18$ cycles per sec., $M = 18\ 1/18$ cycles per sec., and $N_s = 25$ r.p.s.

Thus from equation (10)

$$n = \frac{H-M}{N_s} = \frac{168\ 1/18 - 18\ 1/18}{25} = 6 \text{ nodes}$$

For the case shown in Figs. 40 and 41 an exact analysis is difficult because where the higher frequency comes out clearly the machine has doubtless increased slightly in speed, due to the sudden dropping of the 6500-kw. load. There can be no doubt, however, that the following interpretation is very close to the truth.

$$H = 130\tfrac{1}{2} \text{ cycles per sec., } M = 10\tfrac{1}{2} \text{ cycles per sec., } N_s = 30 \text{ r.p.s.}$$

$$\frac{H-M}{N_s} = \frac{130\tfrac{1}{2} - 10\tfrac{1}{2}}{30} = 4 \text{ nodes}$$

"Feathering" Action of Buckets a Possible Cause of Traveling Waves

Thus far nothing has been said about the cause of vibration in the two cases just described. Further study brought out the fact that waves of this sort rarely occur in turbine disk wheels and the phenomenon is confined to unusually thin types of wheels in which waves are easily built up. After these films were analyzed, a satisfactory explanation of the cause was sought. Referring to Fig. 42 in which the circumference of the wheel disk is formed into a wave shape, the relative angular twisting of the two buckets *A* and *B* will be somewhat as shown. It will be seen that the axial component from the energy left in the steam at the point of leaving the buckets as shown at *C* and *D* will be greater at *C* than at *D*, both reactions being toward the left in the diagram.

Assuming the wheel to be stationary in space and the wave form to move upward in the wheel to a new position as indicated by the dotted line, it will be seen that the buckets *A* and *B* are moved to the positions shown dotted. This means that the force *C*, which is larger than *D*, is operating on the bucket *A* in the direction that *A* is moving due to the wave transition. At the same instant the force *D* is opposing the motion of bucket *B* moving toward the right due to the wave transition. However, since the forces acting in the direction of bucket motion, as at *C*, are greater than the forces opposing the bucket motion, as at *D*,

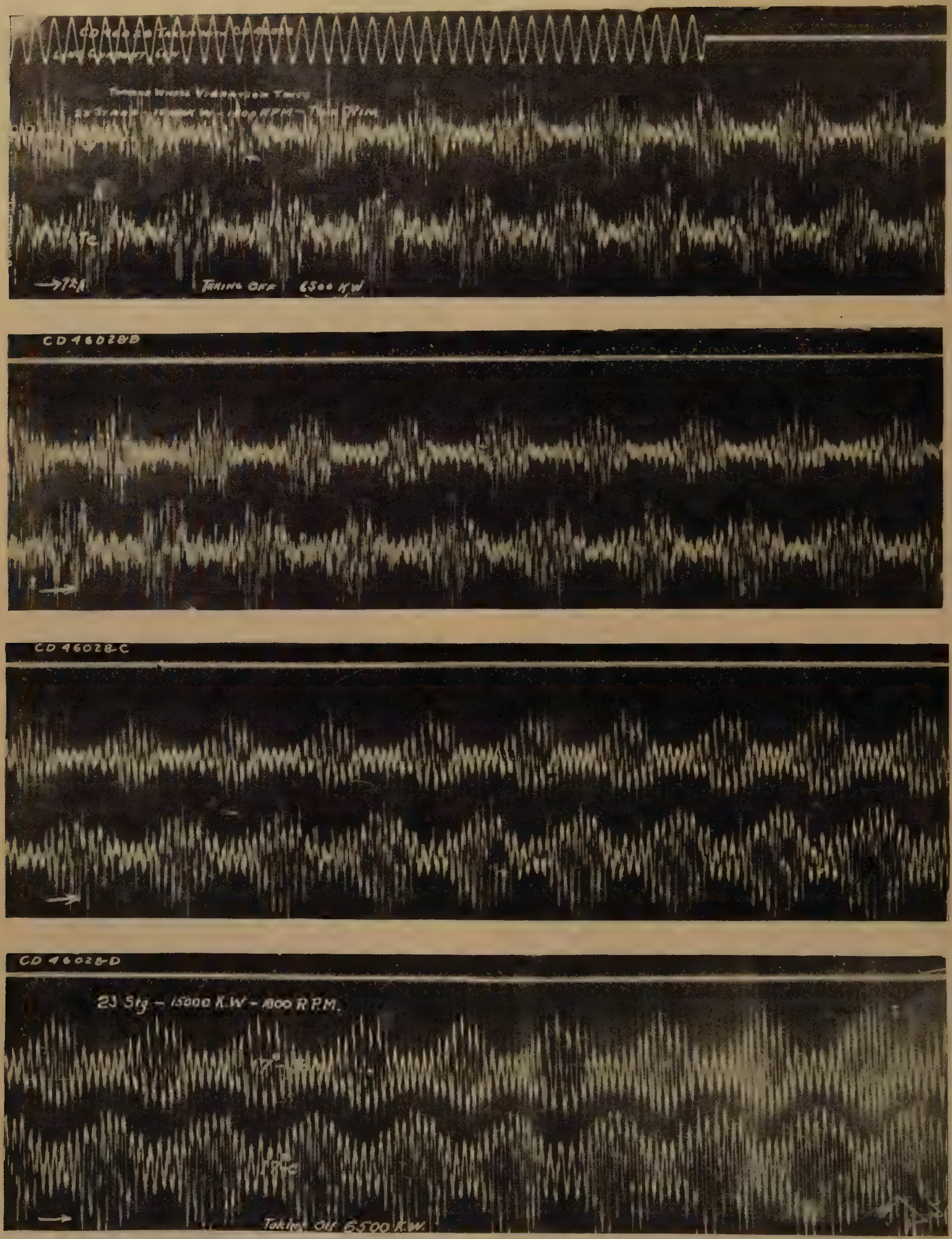

Fig. 41. Oscillograph Records Made by 17th Stage of 15,000-kw., 1800-r.p.m., 23-Stage Turbine

(The upper curve is the 60-cycle line current. The other two curves were made by stationary coils 90 deg. apart. 4-node forward- and backward-traveling waves are indicated.)

it is clear that energy is added to the maintenance of the wave form after it has been initiated.

Fig. 43 was taken from an apparatus specially designed to illustrate the action just described. A small thin sheet-metal disk about 18 in. in diameter was supplied with model turbine buckets around the circumference. This was carried on a shaft mounted in bearings with a small prony brake fitted to the same shaft. A model diaphragm with uniform nozzle openings around the entire circumference was secured to an air-tight box and placed in position to drive the wheel. Air pressure at 5 lb. per sq. in. could be supplied to this diaphragm. The following demonstration was made:

(1) The prony brake was secured to prevent rotation and the air turned on so that it passed through the nozzles. No vibrational effect was noted on the wheel.

(2) The wheel was struck with a piece of wood and was found to shiver and finally come to rest.

(3) The wheel disk was rubbed with a stick quickly in a circumferential direction and in the direction in which it was designed to run, but still it was found to return quickly to rest.

(4) Upon rubbing the wheel in a similar manner, but in a direction opposite to that in which it should rotate, a wave shape of large amplitude, traveling in a backward direction, was developed, which was maintained as long as the air pressure was applied.

Thus it was proved that, in the case of the model, a backward-traveling wave could be maintained after once being initiated, simply by the passage of the air current through the buckets in the usual manner. The reason just given for the maintenance of the backward wave due to this action can also be used to prove that the forward wave would be damped, as in this case the larger force *C* would be working against the motion of the bucket. This explains why a forward wave was not maintained when the wheel was rubbed in the forward direction.

After the backward-traveling wave was set up in the manner already described, the prony brake was gradually released, allowing the wheel to rotate and gradually pick up speed. The wave shape was still maintained but the velocity of the wave relative to space became slower and slower as the wheel accelerated until finally the wave shape stood stationary in space. An amplitude

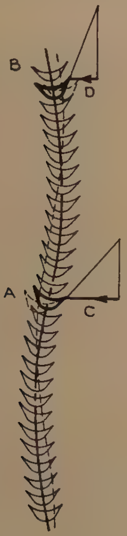

Fig. 42. The Change of Angle or "Feathering" of a Bucket During the Passage of a Traveling Wave Permits the Maintenance of the Wave by Means of Energy Absorbed from the Steam

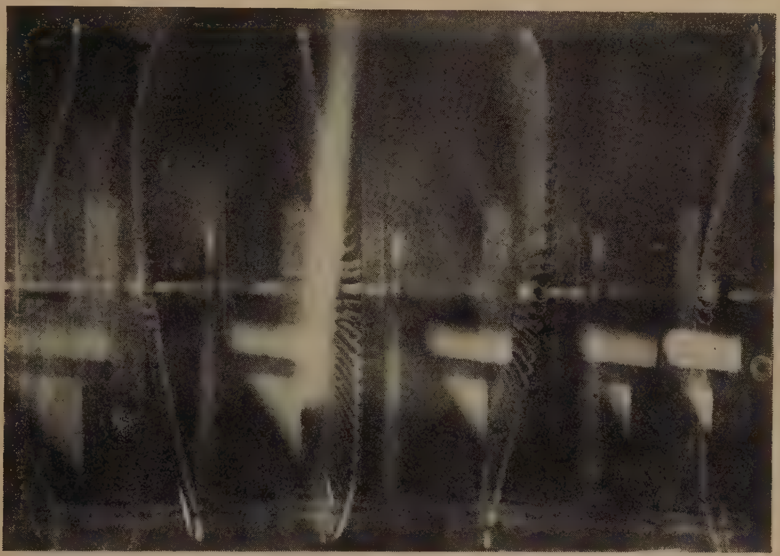

Fig. 43. Successive Pictures of a Traveling Wave in a Single-model Wheel Kept in Motion by High Velocity Air from Model Diaphragm Nozzles

large enough to rub the diaphragm in spots could be built up by slightly increasing the air pressure.

Vibrations Due to Forces of Resonant Frequencies

A rotating turbine disk wheel may readily be made to vibrate with the application of an alternating force corresponding to any one of its resonant frequencies. Fig. 44 shows the frequency-speed diagram of a wheel covering the cases of 4-, 6-, 8-, and 10-node vibration frequencies. Higher vibration frequencies exist, but they are not so important since they are not so readily excited as the lower frequencies. Suppose the wheel to be revolving at a speed of 30 r.p.s. If an alternating transverse force be applied to the rim of this wheel by means of an alternating-current magnet fixed in space, the wheel should vibrate in response to any one of 8 different frequencies *A*, *B*, *C*, *D*, *E*, *F*, *G*, and *H*, corresponding to the speed of revolution of the wheel which, in this case, was assumed to be 30 r.p.s. They are the very frequencies which can be observed for 4-, 6-, 8-, and 10-node vibrations by an oscillograph coil which is fixed opposite the rim of the wheel in the same way as the alternating-current magnet is fixed. They are the *resonant* frequencies of the wheel for 4, 6, 8 and 10 nodes for a pulsating force which acts transversely from a point fixed in space opposite the wheel. It is on this account that only the two curves of the frequency-speed diagram are considered which correspond to a fixed coil in determining these frequencies, namely, the upper and lower curves, corresponding to frequencies arising from forward and backward wave trains. The middle curves represent frequencies which would be observed by a coil carried around with the wheel and have no connection with a fixed coil or a fixed pulsating force.

The points to fix clearly in mind are: (*a*) that a pulsating force of the right frequency applied at a fixed point to a disk wheel revolving at a definite speed may excite wheel vibrations corresponding to any one of a series of resonant frequencies such as *A*, *B*, *C*, *D*, *E*, *F*, *G*, and *H*, as shown in Fig. 44; and (*b*) that these frequencies in each case can correspond to only a single train of traveling waves. For instance, an applied alternating force corresponding to the point *D* is seen from the diagram to have a frequency of 108 cycles per second. Such a pulsating force excites a forward-moving wave train of two waves corresponding to four nodes. This wave is readily built up to a large amplitude. It is not a vibration with radial nodes fixed in the wheel but a train of waves, two in this case.

If a force of a frequency of 12 cycles per second, corresponding to the point *E*, were applied to the wheel, the backward-moving 4-node wave train would build up. The negative frequencies simply mean that the frequency is due to the wave train moving backward in the wheel more slowly than the wheel rotates forward, so the backward wave actually moves forward past a fixed coil and gives a frequency of 12 cycles per second in this case. In the same way pulsating forces of frequencies corresponding to any point on the diagram will develop the wave train for which that point corresponds.

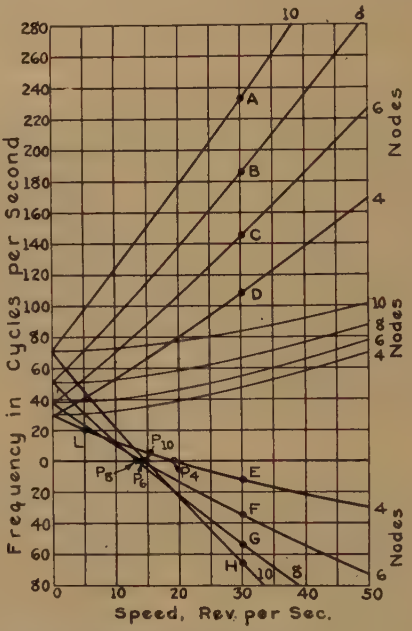

Fig. 44. Frequency-Speed Diagram for 6, 8, and 10 Nodes, 23rd Stage of 15,000-kw., 1800-r.p.m., 23-Stage Turbine

(Points *A*, *B*, *C*, *D*, *E*, *F*, *G*, and *H* show frequencies which would provoke resonant vibration should they occur. P_8, P_6, P_{10}, and P_4 are the wheel critical speeds in the order in which they occur for this wheel.)

For instance, a force of a frequency of 21 cycles per second applied to this wheel when it is rotating at a speed of 5 r.p.s. corresponds to the point *L* on the diagram. This is a point of resonance for a 4-node wave train moving both backward in the wheel and backward in space. The question now arises: To what do the points of intersection (such as P_4 on the 4-node curve) of these curves with the zero frequency line correspond? Here is a wave moving backward in the wheel which registers zero frequency on a coil fixed in space. In other words, a wave train is standing stationary in space because it moves backward in the wheel at the same speed that the wheel moves forward. These waves, although moving in the wheel, are stationary to an observer. This is the most important case of bucket-wheel wave motion, because practically all serious wheel failures have been definitely proved to be the result of this particular type of vibration. This particular condition in turbine wheels will be discussed in greater detail in Part III of this series.

In the present section of the series, two general causes of wheel vibration have been considered: (*a*) a feathering action of the steam on the buckets which may maintain waves; and (*b*) pulsating forces which may cause various resonance responses of the wheel. The first type of vibration is eliminated by the use of wheels of sufficient thickness so that the energy dissipation during vibration is too great to permit a building up of such a vibration. The second type of vibration is eliminated by building the disk wheels so that resonant frequencies are removed so far from disturbing frequencies in the turbine that vibrations do not occur.

Stationary Waves and Critical Speeds of Wheels

It has already been mentioned that the type of vibration responsible for practically all serious wheel failures consists of a train of backward-traveling waves whose backward speed in the wheel exactly equals the forward speed of rotation of the wheel. This results in waves which are stationary in space. Evidently a fixed coil would register no frequency for a stationary wave train, so the presence of such a wave train alone cannot be detected by means of a single fixed coil.

Referring to Fig. 44, the line of zero frequency intersects the 4-, 6-, 8-, and 10-node curves at P_4, P_6, P_8, and P_{10}, respectively. When the wheel is running at the speed of 19.3 r.p.s. corresponding to P_4, the wheel speed and the 4-node wave speed in the wheel are the same so that a stationary wave corresponding to a backward-traveling wave train of four nodes may easily be built up. A small amount of energy may build up a resonant wave train. A wave train made to travel at any other than its natural speed would be a type of forced vibration and has been found to require great force to maintain it. Every turbine wheel has a series of particular speeds for which the speeds of wave trains of 4, 6, 8, 10 nodes, etc., corresponding to 2, 3, 4, and 5 waves, etc., are equal to the speed of the wheel.

These particular speeds of a turbine disk wheel are called *wheel critical speeds*, because it is found that when a turbine wheel is running at any one of these speeds, it is possible for a wave train of large amplitude to develop which may cause the wheel to fail. In other words, turbine wheels are liable to develop stationary waves, but stationary waves can occur only at particular speeds of the wheel, called critical speeds, one for each type of wave train: P_4, P_6, etc., in Fig. 44 are some of the critical speeds for this particular wheel. Others exist for higher numbers of nodes, but these have not been found to be so serious.

Probable Cause of Stationary Waves

Thus far little has been said about the cause of the development of stationary wave trains at wheel critical speeds. That turbine wheels may develop this particular type of vibration with comparative ease is beyond question, because these wave trains may develop during test *without the application of any special external force*. When once the nature of these stationary waves is well understood, however, the cause of their development is not difficult to assign.

It has been stated that traveling waves could be excited by a pulsating force fixed in space, having a frequency corresponding to the speed of the waves past it. When the wave train is stationary in space, the pulsation of the force plainly is no longer required. In other words, a spot of extra pressure is sufficient to maintain a stationary wave. It is found that the application of a fixed force of only a few pounds, such as a small direct-current magnet or a small steam jet, to the side of a turbine wheel causes it to respond strongly at a whole series of critical speeds, even up to critical speeds corresponding to 16- or 18-node wave trains of eight or nine wavelengths on the wheel, and it responds only at critical speeds. It can be shown by calculation that such a force of only two or three pounds may give a continuous supply of energy to a standing wave train, and that this energy, despite the small force, may easily amount to 40 or 50 watts.

Tests on the energy necessary to maintain vibrations of various amplitudes in turbine disk wheels show that this amount of energy may readily maintain a wave train of four or six nodes, of amplitude sufficient to cause serious trouble. Furthermore, small amplitudes which can be detected by oscillograph coils during test may require no more than a few watts of energy to maintain them.

This statement seems amazing in connection with a steel turbine disk wheel, but it has been definitely proved by tests. When we consider a wheel operating in a turbine under the action of steam, it hardly needs to be said that the slightest irregularity in the nozzles might result in a transverse steam force on the wheel a few pounds greater from some nozzles than from others. Only a few pounds difference is sufficient to cause serious trouble in a wheel running at a critical speed. Therefore, wheels must be so designed that they do not operate at any of their critical speeds, as there is always a possibility of such small forces being present in turbines.

Importance of Critical Speed

Clear evidence of stationary waves has been observed in certain cases of failure and also in some cases where failure has not resulted. Scorings were produced on the diaphragm in spots, 180 deg. apart or 120 deg. apart, by the neighboring wheel, the high spots of the stationary wave actually rubbing the diaphragm and producing marks. Figs. 12 and 13* show a case where the 17th-stage diaphragm of a 30,000-kw. turbine is badly scored in two spots 180 deg. apart. These were doubtless caused by a 4-node stationary wave. Fig. 45 shows the 11th-stage diaphragm of a 30,000-kw. turbine, on which three scorings appear due to a 6-node stationary wave train.

In several cases similar rubbing has occurred on the diaphragms on each side of the wheel, there being an equal number of spots cut on each side, the spots on the exit side alternating with those on the entrance side. In these cases of local diaphragm rubbing, the wheel has rubbed around its entire circumference.

While such occurrences point toward standing waves as being a possible cause of trouble, the most convincing evidence of all as to the importance of critical speeds is given in Table II.† Nearly every case of wheel and bucket troubles on record shows a coincidence between some particular wave speed in the bucket wheel and running speed. Furthermore, many tests on actual turbine wheels in the vibration-testing machines have confirmed the truth of this conclusion.

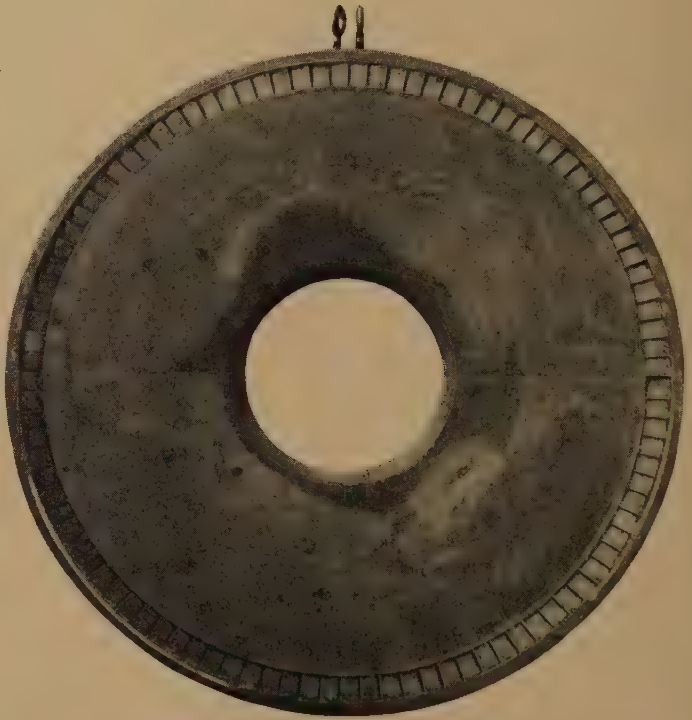

Fig. 45. 11th-Stage Diaphragm of 30,000-kw., 1800-r.p.m., 17th Stage Turbine Showing Scorings Produced by Rubbing of the Shroud Band of the Neighboring Wheel at Three Equidistant Spots 120 deg. Apart Just Outside the Nozzles Due to a 6-Node Stationary Wave at Critical Speed

Vibrations from the Viewpoint of Energy

The determining factor in the building up and maintenance of vibrations and waves is the relation between energy supply and dissipation. Given a certain supply of energy tending to build up waves and a small amount of dissipation of the wave energy per unit of amplitude, the amplitude of the wave will be large. Given a large amount of dissipation of energy, the wave amplitude will be correspondingly small.

Two ways of preventing vibrations of waves therefore appear: (*a*) Decrease the possibility of absorption of energy in wave production; (*b*) increase the dissipation of the wave energy.

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[*] See General Electric Review, June, 1914, p. 357.

[†] See General Electric Review, June, 1924, p. 360.

Both methods are used in the production of disk wheels. The first is used by so adjusting the wheel vibration frequencies that critical speeds are avoided. Critical speeds, looked at from the energy viewpoint, are simply speeds at which the wheel easily absorbs wave energy. The second method is used in the increased thickness of disk wheels, whereby the dissipation of vibration energy may be greatly increased.

When a wave train of constant amplitude is maintained in a disk wheel, the energy dissipated must equal the energy supplied, otherwise the amplitude would not remain constant. The appreciation of this fact makes it possible to find the actual supply of energy necessary to maintain a given wave train by a measurement of the dissipation. The energy supply in maintaining waves in a disk wheel cannot be directly measured as it comes from forces in the turbine during operation about which little quantitative information is available. The energy dissipation, however, may be directly measured by a test on the wheel outside of the turbine.

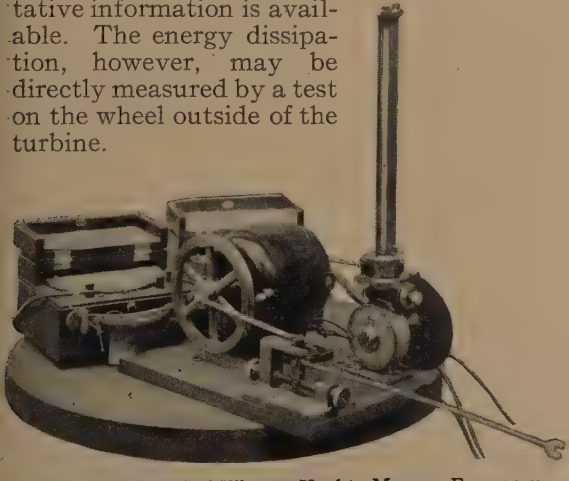

Fig. 46. Mechanical Vibrator Used to Measure Frequency and Energy Required to Maintain Vibration of Turbine Disk Wheels

Measurement of Rate of Energy Dissipation in a Vibrating Disk Wheel

The rate of energy dissipation was first measured by means of the apparatus shown in Fig. 46. A periodic force was applied transversely to the edge of the turbine wheel through the rod indirectly connected to the crankpin of the motor-driven flywheel. The speed of the motor was adjusted until the turbine wheel vibrated in resonance. The energy input to the motor is the sum of the energy required to maintain vibration plus all of the losses. This amount of energy was found to be about 80 watts for a 125-in. diameter turbine wheel vibrating in four nodes through a total amplitude of $\frac{3}{8}$ in. Therefore the energy dissipated in the wheel cannot be over 80 watts, and if corrections are made for losses it appears to be of the order of magnitude of 50 watts.

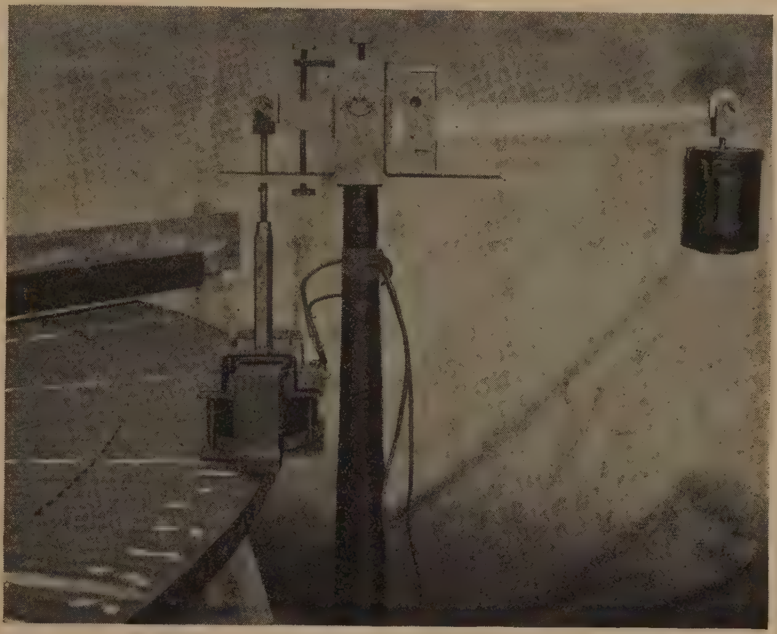

Fig. 47. Balance for Measuring the Energy Dissipated by the Vibration of a Turbine Wheel

In order to confirm these measurements another method was tried in which the vibration energy was supplied to the wheel by means of an electromagnet suspended from the end of a balance beam as shown in Fig. 47. The frequency of the alternating current supplied to the magnet was adjusted until the wheel vibrated in resonance. When the maximum possible amplitude of vibration for a given amount of excitation of the magnet was obtained, the *average* pull on the magnet was weighed directly. Assuming that the pull varies according to a sine-squared law from zero to a maximum of twice the average value (that is, neglecting the effect of variation of the air gap) the rate of energy supply to the wheel can be computed from the frequency and amplitude of motion.

The advantage of this method of test is that practically all losses in the apparatus used to make the measurement are eliminated. The energy supplied is calculated directly from the product of the applied force and the motion of the wheel edge at the point of application of the force, integrated over the required number of vibration cycles. The only source of external loss is through the pedestal on which the wheel is supported. It was concluded that this was small, because, as far as could be measured, for several different types of pedestal the wheel dissipated the same amount of energy.

Fig. 48 shows curves of energy dissipation for 4- and for 6-node wave trains for a medium thin last-stage disk wheel. The energy dissipation is seen to increase about as the square of the increase of amplitude of vibration for small amplitude and at a more rapid rate for larger amplitudes. The energy dissipated by the air friction is comparatively small. The larger part of this energy is dissipated by internal friction within the steel itself due to the repeated bending.

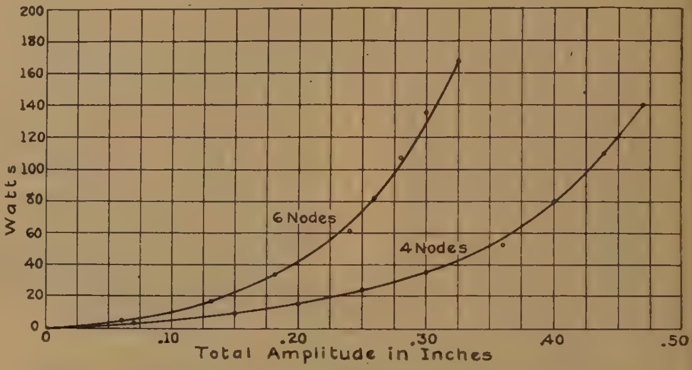

Fig. 48. Curves Showing Relation Between Energy Dissipated and Total Amplitude of Wave Train at Shroud Band

The curves show how very small an amount of energy is required to maintain small amplitudes of vibration. For a total amplitude of 1/10 in. at the bucket tips, four watts will maintain a 4-node wave train, and ten watts will maintain a 6-node wave train at this amplitude. For a ¼-in. amplitude, however, 24 watts is required for the 4-node wave train, and 73 watts for the 6-node wave train.

Calculated Rate of Supply of Energy in Maintaining Waves in Turbine Wheels

The rate of supply of energy to turbine wheels in the maintaining of waves has been calculated for waves built up by the feathering action of steam on the wave forms in the buckets, described elsewhere, and for a stationary wave train built up by a spot of extra transverse pressure. These calculations show that for waves built up by bucket feathering the energy supply varies as the square of the amplitude, but for waves built up by a fixed pressure spot, which comes into action at critical speeds, the energy supply varies directly as the amplitude. The latter effects are consequently relatively large at small amplitudes as shown in Fig. 49 where Curve *II* represents a larger energy supply than Curve *I* for amplitudes below that corresponding to the point of intersection of the curves at *P*. According to this analysis a reason why stationary wave trains developed by pressure spots are more serious than traveling waves due to feathering is that the feathering cannot come into effective action until the wave train has reached a certain amplitude. To initiate a wave train the transverse pressure spot is the more effective.

Since stationary wave trains have been found to be the primary cause of turbine wheel failures, and since the building up of a stationary wave train is believed to be due to the second of the two causes of wave development presented, an indication of the manner in which a fixed force may supply energy continuously to a stationary wave train will be presented.

Fig. 50 represents the developed edge of a turbine wheel carrying a 4-node wave train stationary in space. The wheel edge is shown moving to the right with a velocity *V* and the wave is traveling to the left in the wheel with the same velocity, so that it stands stationary in space. Assume a fixed force *F* acting at a nodal point as shown. At this point a particle *P* has a component of motion in the direction of this fixed force equal to V_F in the diagram. The product of this velocity and the force *F* gives the rate at which work is done on the particle at this instant. Since the force is fixed in space it acts first on one particle and then on the next as the edge of the disk wheel moves along, but it does work continuously at this rate. This is therefore the rate at which work is supplied to the wheel in building and maintaining the wave train.

It is easily shown for a sine wave that the value of this transverse velocity component is

$$V_F = \frac{2\pi V y_0}{\lambda} \qquad (11)$$

where y_0 = half amplitude of the wave
λ = wavelength
V = velocity of the wheel edge or of the wave.

Multiplying this velocity component by the force F, the work per second supplied to the wave is

$$W = \frac{2\pi V y_0 F}{\lambda} \qquad (12)$$

In the tests described it was found that when $y_0 = \frac{1}{4}$ in., W may be about 25 watts. Taking average values for V and for λ, it is found from equation (12) that a force F of only a few pounds may supply the required 25 watts to the wheel.

This equation assumes the force to be concentrated at a point. If the force is distributed over half a wavelength, the total force required will be somewhat larger.

Utility and Limitations of Theoretical Design

As will appear subsequently, the actual process of design, aside from wheels of totally new characteristics, is a process of comparison with a carefully correlated catalog of all previous similar wheels. Such a process, checked by test, is thoroughly logical, and proves to be satisfactory. In fact, for reasons which it is the intention of this section to make clear, comparative selection and test is the only satisfactory means of design known at this time. Such a method is comprehensive.

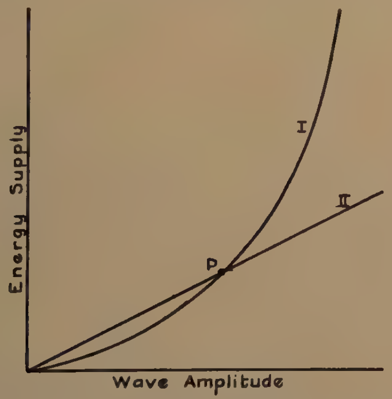

Fig. 49. Relation Between Energy Supply and Amplitude of Wave

(Curve *I* is for a traveling wave, while Curve *II* is for a stationary wave. From the shapes of the curves it is seen that the latter may *originate* more easily.)

Even now shapes proposed by theoretical means come within the scope of the testing organization for verification. And new shapes in which theoretical analysis is most needed are, unfortunately, by that fact most subject to variation from theory and, therefore, especially need to be checked. Similarly the wheels of ordinary design which need least to be checked are most susceptible of calculation. It is entirely conceivable that at some future time material specifications can be made sufficiently rigid, machine work sufficiently exact, and methods of assembly so precise that every wheel can be constructed under conditions of uniformity sufficient for a general dependence on theory. At the present time it is unsafe to accept the successful calculation of nine out of ten wheels as evidence that the tenth wheel also will be correct.

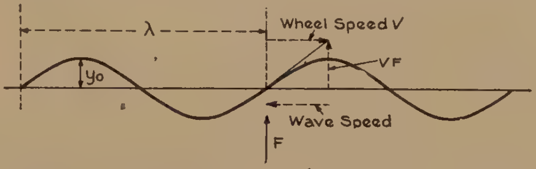

Fig. 50. Developed Edge of a Rotating Wheel Carrying a Wave, Stationary in Space. The fixed force *F* supplies the energy that maintains the wave

It seems unnecessary to give here in full the elaborate theories developed during these investigations, but no adequate idea of the importance of actually testing wheels can be had without a thorough understanding of the scope of the various means of design tried. Space must be given, therefore, to a description of the theory and the tests made in its verification.

The simplest elastic system considered was a simple cantilever bar or beam of uniform cross-section, similar to a vibrating reed. This system is capable of a complete analytic treatment, from which the shape during vibration and the exact frequency can be obtained. The latter is what is of interest here and it may be written

$$F = \frac{1}{0.569\pi}\sqrt{g\frac{EI}{wl^4}} = \frac{3.18t}{l^2}\sqrt{\frac{E}{\delta}} \qquad (13)$$

in which

F = frequency, cycles per sec
g = gravity, in. per sec. per sec.
E = Young's modulus, lb. per sq. in.
I = moment of inertia of cross-section, in.^{4}
w = weight, lb. per in. length of bar
l = length, in.
t = thickness of rectangular bar, in.
δ = density of steel, lb. per cu. in.

In making a verification of this formula the dimensions and weight of the bar may be easily measured. For the same material the frequency should vary directly as the thickness and inversely as the square of the length. Fig. 51, curves *A*, *B*, and *C*, show a series of three tests made in an unsatisfactory attempt to prove this simple rule. All bars were of steel, but no particular attention was paid to getting the same stock. The thickest bar *B* actually shows a progressive deviation and suggests a variation with $l^{1.9}$ instead of l^2. The last test *C* was made with two bars balanced like a fork, and while this test is better, it was not considered satisfactory for such a simple rule. Therefore, the test represented by curve *D*, Fig. 51, was made with a ½-in. square bar clamped directly to the heavy cast-iron floor of the shop. The modulus of elasticity was separately determined by a deflection test as a simple beam. The plotted points show agreement with the theoretical line over a 10 to 1 range of frequency variation, but even with this clamp the agreement starts to fall off at frequencies of about 300 cycles per second.

These simple tests have been described thus at length in order to show that laboratory care is necessary in the simplest cases in order to secure frequencies within one or two per cent of theoretical expectations.

Turning next to the question of disk wheels, the theory of vibration will be described. In previous sections it has been made clear that, so far as the frequency of various particles of the disk is concerned, it makes no difference whether the disk is subject to traveling waves or whether it vibrates with fixed nodes. In either case the natural frequency is the same, and all that is essential is a solution capable of giving the frequency of vibration in each of the various natural types.

The problem of vibrating flat plates is thoroughly discussed by Lord Rayleigh,[1] but the complexity of a turbine wheel is somewhat beyond the formulas developed. Stodola[2] gives the formula for a flat circular plate based upon Kirchhoff's contribution to *Crelles Journal* in 1850, as

$$F = c\frac{t}{r^2}\sqrt{\frac{E}{\delta}} \qquad (14)$$

in which r = radius of plate, in.

c = a constant depending on the nodal configuration and Poisson's ratio.

Stodola then goes on to examine at some length a method attributed to Ritz[3] in which the principle of least work is employed. Finally he selects a principle noted, in passing, by Rayleigh,[4] which proves to be the most practicable for use so far found.

Rayleigh's principle is that "The period calculated from any hypothetical type cannot exceed that belonging to the gravest normal type." (Section 89.)

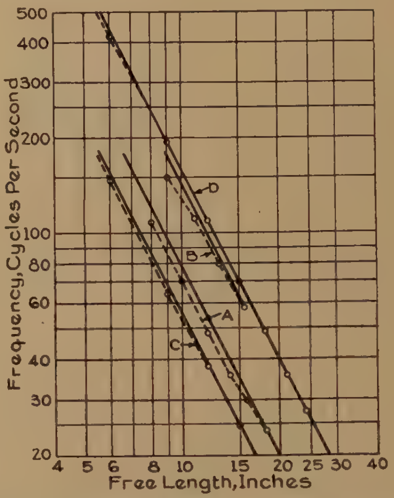

Fig. 51. Vibration of Steel Bars Fixed at One End

(Full lines show theoretical variation of frequency. Broken lines show deviations in test.)

Bar A is 1.49 in. by 0.245 in.
Bar B is $\frac{7}{16}$ in. square.
Bar C is a 2-bar adjustable fork 0.86 in. by 0.180 in.
Bar D is ½ in. square.

The indicated method of calculation is to assume any hypothetical shape of deformation and calculate its true potential energy. Equate this to the maximum kinetic energy which the system would have if it could vibrate in the hypothetical shape, and the period so calculated cannot exceed the gravest natural period. Plainly the assumed shape which gives the longest period is nearest to the true condition.

In applying this method Stodola represents the wheel by a hyperbolic profile and makes ingenious allowances for the stiffness of the wheel rim and the weight of attached buckets. The hypothetical shape is sinusoidal about the circumference and along a radius it is an exponential curve. The potential and kinetic energies are formulated and the frequency of vibration expressed in terms of the foregoing quantities and made a function of the exponent of the radial-deflection curve. Then by a differentiation the exponent leading to the minimum frequency (or gravest period) is selected. All of these steps are well justified.

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[1] The Theory of Sound, 1894.

[2] Ueber die Schwingungen von Dampfturbinen-Laufrädern. *Schweizerische Bauzeitung*, May 2, 1914.

[3] *Crelles Journal*, 1908.

[4] The Theory of Sound.

on a theoretical basis. Rayleigh shows that there can be a considerable variation of the hypothetical from the true shape without greatly affecting the result. The exponential shape is, in itself, a reasonable approximation, but the Stodola method selects not only the exponential shape but uses that exponent best suited to the case in hand.

In reviewing the various points of attack another plan may be mentioned which has not yet been worked out for application although its very simplicity commends it if it were as easy to construct the deflection curve for a disk wheel as for a rotor shaft. Since the idea of natural vibration supposes that the motion of all particles is both harmonic and isochronous, it follows that in the case of every particle, irrespective of displacement or time, the same ratio exists between weight and force per unit displacement, because all particles have the same period. In other words, if the material is all alike and all particles are of the same weight, the force per unit displacement is the same throughout the system. If the system is a shaft of uniform section or a plate of uniform thickness, the shape taken will always be such that at every point the unbalanced force (shear) on an element of length or surface will be strictly proportional to the deflection. In the case of a shaft or a reed where a deflection curve can be easily constructed by graphic processes, the indicated procedure is to assume a loading, construct the corresponding deflection curve and then alter the loading, and repeat until by successive approximations, agreement of proportionality is secured between deflection and load.

Then the relation between change of shears in any part of the length, deflection and weight of the same section determines the frequency of the system. The method would be identical with that used in calculating the critical speed of rotation of a shaft. In the case of a vibrating disk wheel the shape within the rim is such as would be taken under a loading per unit area proportional to the product of deflection and thickness.

The Rayleigh principle has been developed along three different lines by the General Electric Company. The first frequency calculations were made by adapting the formulas of Stodola directly to the wheels in question. Charts of coefficients, tables, and printed forms were provided, and some hundreds of wheels were calculated in this way with good success. Usually wheels of nearly hyperbolic profile with standard rims and one row of short buckets or medium-length buckets were easily and quickly computed by this method. There were, however, many important wheels with long buckets which failed to check the calculated frequencies. The protection of every wheel without exception was necessary. The difficulties were sought in variation of the actual profile from the assumed hyperbolic shape, in the action of the rim, in the bending of the bucket, and in the consideration of the bucket dovetail, and the wheel hub. These are the reasons that account for subsequent developments of calculation methods. That other troubles of a more serious nature were also accountable for the discrepancies will presently be shown.

In order to take account of the various items to which the troubles of analytical calculation were attributed, two other methods were developed in one of which the Rayleigh principle was applied graphically. By this method the true wheel shape is plotted and a deflection curve assumed without restrictions as to type. The wheel profile is divided into a series of sections and the kinetic and potential energies of each section are calculated and the frequency found by equating the summations. Of course a variety of deflection curves have to be examined until that giving the minimum frequency is found. Although standard calculations forms are used, the method is laborious as compared with analytic work, but it is comprehensive and sound in principle and with similar assumptions and limitations the two methods give exactly the same results. A limited variety of wheels, which, however, includes standard types, can be satisfactorily calculated by the analytic method. But wheels of limiting designs or peculiar contour require the more elaborate method.

The third method used the Rayleigh principle as developed by Stodola, but faced the fact that wheels are not necessarily hyperbolic in shape. This method was adapted at the outset for tabular calculation in order that a wheel of any profile might be handled. In various other details, the process of application differed slightly. These various methods have been applied and in many cases give satisfactory results. The important thing left is to find out what is the matter with the wheels for which the theory is inadequate.

In the case of the cantilever bar it was found very difficult to secure tight clamping. From bars the investigation was extended to flat circular plates. Kirchhoff's formula has already been cited, showing that for uniform material the frequency should vary in direct proportion to the thickness and in inverse proportion to the square of the radius. A series of tests was made on four plates to verify this rule.

The results are shown in Figs. 52, 53 and 54 for four, six, and eight nodes, respectively. The letters *A*, *B*, *C*, and *D* are used to designate the four pieces of metal used. The left-hand curves show the variation of frequency due to change in diameter for ⅞ in. and ¼ in. thickness. The right-hand curves show the variation in frequency due to change of thickness for disks 50 in. in diameter. The *A* plate was tested but once and, as it agreed with the calculation, it is plotted as a master point from which the full lines representing theoretical relations are drawn. The *B* plate was 50 in. in diameter, and it was tested with thicknesses of 1 in., ⅞, ¾, ½, ⅜, and ¼ in. Note that when 1 in. thick, this wheel vibrated in substantial agreement with theory, but when ½ in. thick the 4-node frequency was too low by 33 per cent. Note also that the *C* plate when 50 in. in diameter had a 4-node frequency more than 40 per cent too high, but as the diameter was subsequently reduced to 40, 30, 25, and 20 in. the agreement became better. It is also noteworthy that the agreement is better, the larger the number of nodes. Now note the plate *D*, 30 in. in diameter and ¼ in. thick. The expected 4-node frequency was 56. The measured value was 73, which is 30 per cent too high. This plate was subsequently "annealed" but the effect of this heat treatment was to reduce the 4-node frequency to 31, or less than half of its previous value, and 45 per cent too small as compared with expectations.

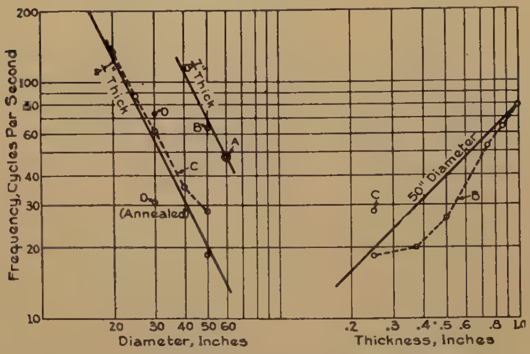


Fig. 52. 4-Node Frequency of Flat Circular Plates

(Full lines indicate theoretical relations. Broken lines show deviations in test. *A*, *B*, *C*, and *D* indicate the four different pieces of steel used.)

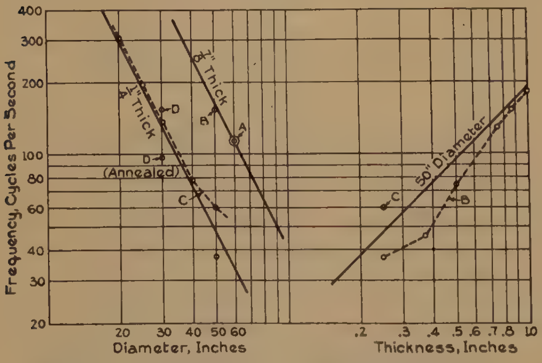


Fig. 53. 6-Node Frequency of Flat Circular Plates

(Full lines indicate theoretical relations. Broken lines show deviations in test. *A*, *B*, *C*, and *D* indicate the four different pieces of steel used.)

It had been noted that the same piece of metal—when altered in thickness or diameter—varied widely in the amount of its divergence from theory, far more widely than could be accounted for by variation in elastic modulus or density. It seemed probable that the condition of initial internal stress in the plate was changed by the removal of certain stressed portions of the material. It was difficult to account for the variations otherwise. Widely varying methods of support had failed to have appreciable effects. After the *D* plate had been put through a heat treatment intended to anneal it so as to remove internal stress, with the result that its frequency was reduced more than half, it appeared necessary to accept the idea of internal stress to explain the fluctuations. The easiest way to vary the condition of internal stress was to vary the temperature distribution.

A momentary application of a gas flame to the center of the disk *D* changed the frequency from 31 to 65, more than double, this frequency being measured while there was a temperature gradient along radial lines. The resulting internal stresses had the expected effect on the frequency which dropped as the temperature became more uniformly distributed throughout the disk. It is

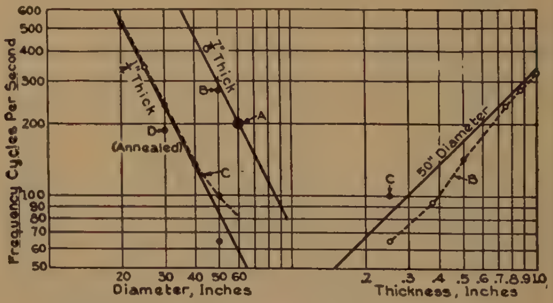


Fig. 54. 8-Node Frequency of Flat Circular Plates

(Full lines indicate theoretical relations. Broken lines show deviations in test. *A*, *B*, *C*, and *D* indicate the four different pieces of steel used.)

comforting to note that the fluctuations shown in the test plates of Figs. 52, 53 and 54 are extreme and appear much less severe in thicker plates. Most turbine wheels are of such proportions as to be less subject to variation of frequency on account of internal stress.

This series of simple experiments furnishes easily understood evidence that one of the factors of prime importance influencing the natural frequency of turbine wheel vibration is the exact condition of internal stress. It is also plain that on this account very refined methods of material treatment, machining, and assembly must be developed so that perfect uniformity can be assured before the practice of keeping a strict watch of every wheel for fluctuations from expected frequencies can be superseded. A very considerable amount of information has already been cataloged in explanation of frequency variations by the test methods in use.

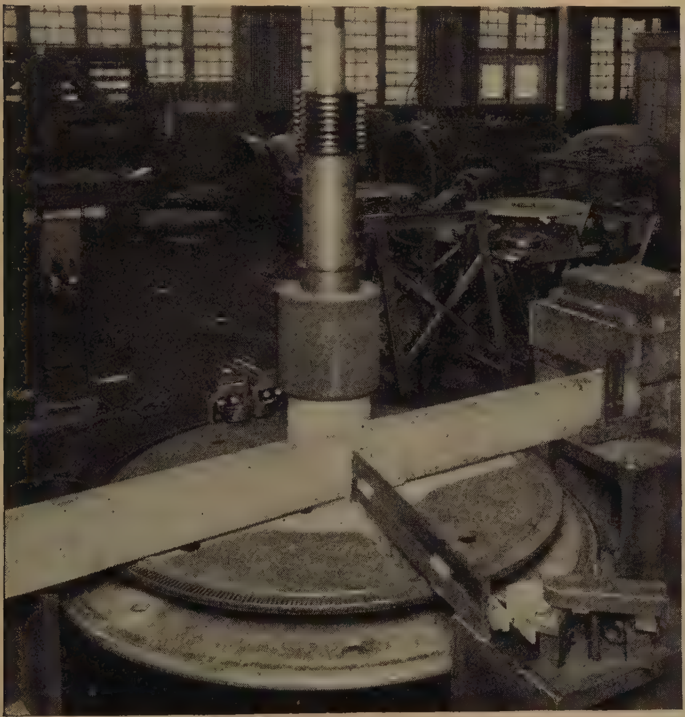


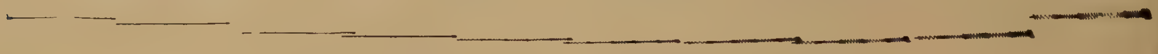
Fig. 55. Smoked-Glass Apparatus for Measuring Amplitude of Vibration of a Turbine Disk Wheel

Measurement of Deflection Shape During Vibration

The determination of stresses due to vibration in a vibrating disk wheel is easily found from the deflection shape of the wheel. Once the shape is known, the stresses can be calculated by well-established formulas. It will be remembered that the determination of frequency by the methods described also implies a knowledge of the deflection shape from which the potential and kinetic energies are calculated. The deflection shape is, therefore, vital to a knowledge of the problem.

In order to make actual measurements of the radial shape during vibration the apparatus illustrated in Fig. 55 was constructed. A frame fitted with guides in which a long plate glass could be inserted was placed on a radial line with the glass perpendicular to the surface of the plate, diametrically opposite to the magnet in order to secure the record mid-way between nodal radii. The frame was rigidly supported independently of the wheel at each end. Phosphor-bronze indicators, each carrying a needle-point stylus, were rigidly fastened to the wheel with a mixture of resin and beeswax. The glass was coated with lamp-black. The needle contact was controlled by a tangent screw at the outer end of the frame. While the wheel was vibrating, the plate was pushed radially and each needle recorded a wavy curve. A stop plug makes it possible to take four to six records on a single glass, each record containing five to ten waves for each needle. Several series of corresponding waves are selected and the amplitudes at the various needles are measured directly from the smoked glass by means of an optical micrometer. Fig. 56 shows photographic prints made from the smoked glass records. Fig. 57 shows a series of deflection curves for various nodal configurations made on a special wheel of truly hyperbolic profile. Fig. 58 shows the curves measured for the *B*-plate wheel referred to before when 50 in. in diameter by 1 in. thick. In addition it shows the curves selected by the Stodola process for calculation. It will be noted that, while not exact in shape, the agreement is very good, in fact as far as the frequency calculation goes, very little difference can be distinguished.

The calculation of stress requires a better knowledge of the deflection shape than does the calculation of frequency. The smoked-glass method has been of especial value in furnishing a process for measuring deflection and thus indicating stress. When the deflection shape is known the stresses are given by the formulas for a bent plate deformed in two directions. It is not always possible to determine from resonant frequencies what type of vibration has caused a failure because more than one type may have a frequency not far from running speed. In case of certain failures a stress analysis can sometimes show definitely that only one of the nearly resonant types could possibly have produced the failure.



Sixteenth-stage Wheel on shaft; 6-node vibration, frequency 131.3

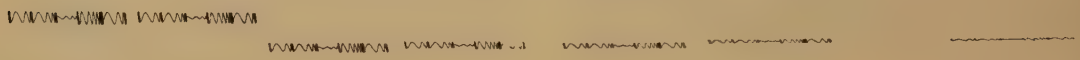
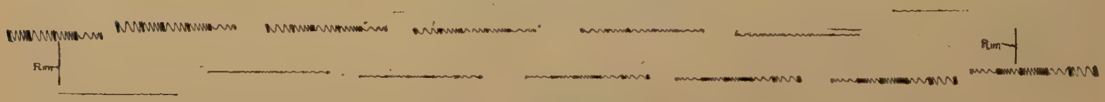


Plate Wheel clamped on rubber supports spaced 90 deg. apart about 10 in. from center; 4-node vibration, freauency 48.8



Hyperbolic Wheel on shaft; 4-node vibration, frequency 82.35

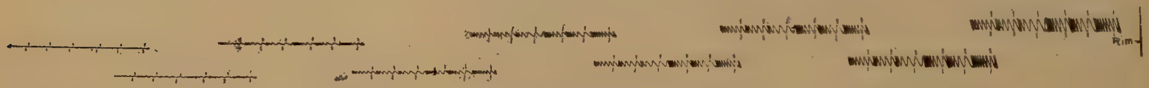


Plate 50 in. in diameter, 1 in. thick, clamped by bolt through 1 in. hole in center; 4-node vibration, frequency 78.2

Fig. 56. Photographic Contact Prints of Smoked-Glass Records of Amplitude of Vibration of Turbine Disk Wheels
(The full-sized smoked-glass record is measured with an optical micrometer.)

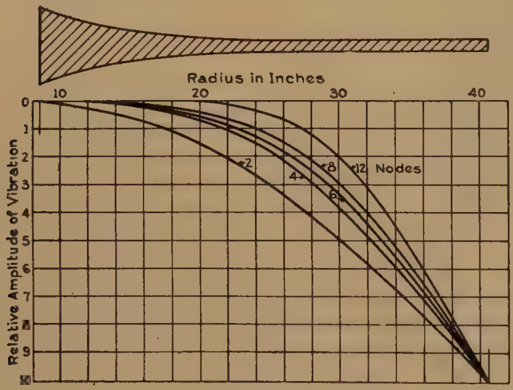


Fig 57. Measured Deflection Curves for a Disk of True Hyperbolic Profile

The utility of stress analysis presupposes a complete knowledge of the strength of the material under conditions of vibration. The subject of fatigue stresses has been the object of many investigations, but usually devoted to completely reversed stresses. At the especial request of the General Electric Company, the University of Illinois Engineering Experiment Station undertook to investigate the case of repeated bending superposed on tension such as exists in a rotating turbine wheel. A variety of heat treatments of turbine steels have been investigated under these conditions and the first results of these experiments are described in Chapter IV of Bulletin 136 of the Engineering Experiment Station of the University of Illinois.

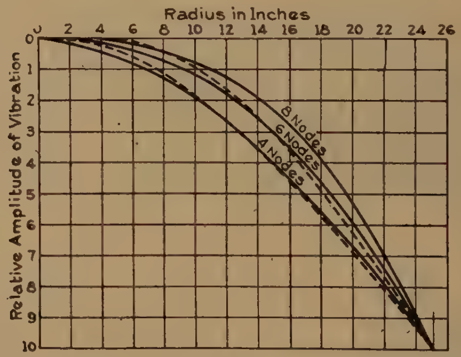


Fig. 58. Comparison of Calculated and Measured Deflection Curves for Plate *B*, 50 in. Diameter by 1 in. Thick

(Full lines calculated by formula $y = aR^s$. Broken lines show measured amplitudes.)

Part III (which will appear in the August issue of the REVIEW*) is devoted to a description of "The Methods of Design and Testing for the Protection of Turbine Disk Wheels from Axial Vibration." This procedure, established for the manufacture and production of turbine wheels, has definitely eliminated difficulties of the type enumerated in Part I.*

The Charles A. Coffin Foundation Award to the Public Service Company of Northern Illinois

When the General Electric Company in 1922 set aside a fund of $400,000 to be known as the "Charles A. Coffin Foundation," in honor of its former President to whom the Company and in fact the electrical industry in the United States owes much of its rapid and sound development, it was determined that one of the purposes of the Foundation would be to give recognition to the public utility operating companies which give the best possible service.

To this end a gold medal, known as the "Charles A. Coffin Medal," is awarded annually to the public utility operating company within the United States which, during the year, has made a distinguished contribution to the development of electric light and power for the convenience and well-being of the public and the benefit of the industry. The Company receiving the medal also receives $1000 for its Employees' Benefit or similar fund.

While the Charles A. Coffin Prize Committee of the N.E.L.A. which made the award did not describe the achievements which resulted in the award, the following accomplishments of the Public Service Company of Northern Illinois undoubtedly were determining factors: an intensive program of service to the public throughout the territory in which it furnishes electric light and power, the population of which is half a million; the promotion of its employees' welfare; the building of organization efficiency; and the increase of customer stockholders.

The first of these medals was given last year to the Southern California Edison Company for its achievements during the year 1922.

The present year's award was made on May 21st to the Public Service Company of Northern Illinois because of the meritorious record it made during 1923. The Committee which decided on the award consisted of: Mr. Walter H. Johnson, Chairman, Samuel W. Stratton, and Martin Insull.

This company, during 1923, sought to improve its relations with its customers in several ways. It organized a staff of men to answer complaints by personal calls, doing away with the custom of answering by letter; it inaugurated a policy of furnishing standard 60-watt lamps free in return for burned out lamps; and it placed on exhibition three electric homes, one of which was visited by 46,000 persons.

The company organized during the year a department of public relations, the progressive advertising work of which succeeded in reducing the number of complaints. Newspaper advertising, painted highway bulletins, colored posters, descriptive folders, motion pictures, and the publication of an attractive year book constituted the publicity activities of the company.

For the benefit of its employees this company has an employees' saving fund in which, at the end of five years, employees may receive their deposits in cash, plus compound interest, or in the common stock of the company; free life insurance up to $1500 for employees in the service of the company six months and additional insurance at low rates; an employees' temporary loan plan; and a service annuity plan providing for annual payments to retired employees of not less than $300.

The company believes it is the first electric public utility to co-operate with an educational institution for raising the standard of its personnel. It has an arrangement with the University of Illinois whereby it gives special supervision to graduates of the university's course in the economics of the utility industry, and extends the use of its plant for experimental work.

Employees are encouraged to accept responsibility as good citizens and the company is proud of the fact that among its employees one is a mayor, one is president of a chamber of commerce, several are chamber of commerce directors, one is president of a Kiwanis club and one is chairman of a civic safety organization.

This company operates several generating stations, and in 1923 it completed the first link in a proposed 132,000-volt inter-connection between its larger stations. In 1923 its stockholders numbered 21,000, a gain of 35 per cent over the previous year, and the number of its customers showed an increase of 18½ per cent. The Illinois Commerce Commission graded the company at 93.88 per cent perfect service for the year, an increase of four per cent over the previous year.

The Charles A. Coffin Foundation Award of Fellowships

The terms of the Charles A. Coffin Foundation, established by the General Electric Company in 1922, make provision for the annual award of $5000 for fellowships to graduates of universities, colleges, and technical schools of the United States who have shown, by the character of their work, that they could with advantage undertake or continue research work in educational institutions either in this country or abroad. The fellowships are given in the fields of electricity, physics, and physical chemistry, and the committee in charge (consisting this year of Mr. Charles F. Scott, John C. Merriam, and Harris J. Ryan) awards them to men who, without financial assistance, would be unable to devote themselves to research work.

This year's awards were recently made to eight university men of high scholastic attainment and exceptional promise, as listed below.

Ralph D. Bennett, who was graduated from Union College, Schenectady, N. Y., in 1921 with the degree of B.S. in Electrical Engineering, and was an honor man. He accepted a position as instructor in mathematics at that institution, and while teaching completed a post-graduate course in electrical engineering and mathematics, receiving the degree of Master of Science in Electrical Engineering in 1923. The following fall he entered the Ogden Graduate School of Science, University of Chicago, where he is studying for a doctor's degree. During the coming year he will devote himself to research on a direct test of the quantum theory at the Ryerson Laboratory of that university under the direction of Prof. A. H. Compton.

Ulric Bray, who won high honors at Emory University, Atlanta, Georgia, from which he was graduated with a B.S. degree in 1921. The following year he taught physics and chemistry in Emory University Academy, and in the fall of 1922 became a graduate student and laboratory assistant at the Sterling Chemistry Laboratory, Yale University, where he is engaged in work leading to the degree of Ph. D. He has been studying equilibrium conditions in the system alkali-carbon dioxide-water, and will continue research in this field at the same institution under Prof. John Johnson.

G. Howard Carragan, who attained high scholastic standing while attending the Rensselaer Polytechnic Institute at Troy, N. Y., from which he was graduated in 1918 with the degree of M.E. The same year he joined the army, where he was commissioned a second lieutenant in the Engineering Corps. From 1919 to 1921 he was connected with a Diesel oil engine company as designer and draftsman, and in the last named year entered Chicago University, where he is taking post-graduate work leading to the degree of Ph.D. He will continue research work at the Ryerson Laboratory on the Zeeman effect in fluorine under Prof. Henry G. Gale, dean of the Ogden Graduate School.

Elliott W. Cheney, who was graduated from Dartmouth in 1920 with the degree of A.B., following which he became instructor in physics at Syracuse University. After a year there he accepted a similar position at Brown University, studying for an M.A. degree meanwhile, which he is to receive this year from Brown. He has made an unusual record and expects to enter Princeton this fall, where he will do research work on the electron theory under Prof. K. T. Compton, and will be a candidate for a doctor's degree.

R. Carvel Hensen, who was graduated from the Baltimore Polytechnic Institute in 1920, after which he entered Johns Hopkins University, where he received the degree of bachelor of engineering, standing highest in his class, and is now a candidate for the degree of doctor of engineering. He plans to engage in research work at the same institution, devoting his study to insulation and allied problems, with special reference to absorption, under Drs. J. B. Whitehead, F. W. Lee and W. B. Kouwenhoven.

Clarence T. Hesselmeyer, who maintained a record for high scholarship while in the Leland Stanford Junior University from which he was graduated this year with the degree of A.B. in Mechanical Engineering. He plans to do research work in high-voltage phenomena and in electrochemistry at Stanford under Professors Ryan, Henline, Clark, and Morgan.

Alfred L. Dixon, who was graduated from the University of Illinois with the degree of B.S. in Chemistry and who last year was awarded a Charles A. Coffin Foundation fellowship. He has devoted the last year to research at that university in the measurement of the vapor pressures of zinc and lead at high temperatures, and in the relation between thermoelectric force and electron emission. He receives a master's degree this year. In point of originality and mathematical ability he has been an outstanding student and has shown remarkable ability and technique in carrying out the rather difficult experimental manipulation connected with high temperature research. The fellowship has been renewed for the coming year and he will investigate some phases of electronic and thermodynamic effects at high temperatures under Prof. J. H. Rodebush at Illinois, leading to a higher scholastic degree.

William L. Fink, another man to whom a fellowship was renewed, was graduated from the University of Michigan with the degree of B.S.E. in 1921, receiving a degree of M.S.E. the following year. He then became an assistant to Prof. E. D. Campbell, director of the Chemical Laboratory there. He has made a brilliant record and his work has been highly complimented by his professors. His post-graduate work will lead to a doctor's degree. With the aid of the Charles A. Coffin Foundation fellowship granted him for the year 1923-24, he devoted himself to research work at Michigan, investigating the structure of certain steels by metallographic and X-ray methods. He will follow this same line of inquiry during the coming year with particular emphasis on the effect of carbide concentration, working under the direction of Prof. Campbell who, though blind for some years past, is one of the most prominent scientists in his field in the country.

LIBRARY SECTION

Condensed references to some of the more important articles in the technical press, as selected by the G-E Main Library, will be listed in this section each month. New books of interest to the industry will also be listed. In special cases, where copy of an article is wanted which cannot be obtained through regular channels or local libraries, we will suggest other sources on application.

Arc Welding

Improvements in Arc-Welded Rail Joints. Fehr, R. B.
Elec. Rwy. Jour., May 17, 1924; v. 63, pp. 783-785.
(Abstract of a paper before the Southwestern Public Service Association.)

Bearings

Experience with Bearings and Vibration Conditions of Large Hydroelectric Units. Harisberger, John.
A. I. E. E. Jour., May, 1924; v. 43, pp. 428-429.

Condensers, Synchronous

Use of Synchronous Condensers with Three-Winding Transformers. Bergvall, R. C.
Elec. Jour., May, 1924; v. 21, pp. 205-206.

Current-Collecting Devices

Overcoming Current-Collection Troubles on Steel Wire. Robinson, H. M.
Elec. Rwy. Jour., May 17, 1924; v. 63, pp. 767-769.
(Result of investigations made by the Northern Texas Traction Company, Fort Worth, Texas.)

Electric Meters

Recent Developments in Kilovolt-Ampere Metering. Smith, B. H., and Rutter, A. R.
A. I. E. E. Jour., May, 1924; v. 43, pp. 441-445.
(Describes two late developments in kv-a. demand meters.)

Electric Transmission Lines—Descriptions

Operation of 220,000-Volt Transmission Lines. Copley, A. W.
Elec. Jour., May, 1924; v. 21, pp. 202-204.
(Short description of the Southern California Edison Company's Big Creek lines and the Pacific Gas & Electric Company's Pit River lines.)

Hydro-electric Plants, Automatic

Load Control in Automatic Hydro-Electric Generating Stations. Denny, R. C.
Power, May 6, 1924; v. 59, pp. 716-717.

Insulators

Cleaning Dirty Insulators.
Elec. Rev., May 9, 1924; v. 94, pp. 739-740.
(Describes a special tank for cleaning insulators that have been in use.)

Load Dispatching

Load Dispatching System of P. G. & E. Co. Geiger, C. W.
Power Pl. Engng., May 15, 1924; v. 28, pp. 543-545.
(Describes the system used by the Pacific Gas & Electric Company.)

Mine Hoists

Novel Features of Electric Mine Hoists Recently Installed in Northern Ontario. Haight, H. V.
Elec. News, May 1, 1924; v. 33, pp. 52-55.
(Illustrated description of electric mine hoists having 250-h.p. motors controlled by compressed air.)

Power Plants, Electric

Engineering Features of the Philadelphia Electric Company System. Eglin, W. C. L.
Elec. Wld., May 10, 1924; v 83, pp. 933-950.
(Illustrated account of the various engineering features of the company.)

Repair Shops, Electrical

Winding Standards for a Railroad Electrical Shop. Turtle, Alfred C.
Rwy. Elec. Engr., May, 1924; v. 15, pp. 141-143
(Methods of repairing and testing the coils of various kinds of motor equipment.)

Substations

Railway and Power Substations Combined for Economical Operation.
Elec. Rwy. Jour., May 10, 1924; v. 63, pp. 729-731.
(Short account of the Cicero substation of the Chicago Rapid Transit Company and the Public Service Company of Northern Illinois.)

Turbine-Generators

Heavy Current Turbo-Generators.
Elec'n., May 9, 1924; v. 92, pp. 570, 573.
(Short description of a new Brush-Ljungström machine.)

Voltmeters

Novel Alternating-Current Voltmeter. Wilson, Leon T.
A. I. E. E. Jour., May, 1924; v. 43, pp. 446-448.
(Describes an improved thermo-voltmeter which may be used at all frequencies up to 1,000,000 cycles.)

NEW BOOKS

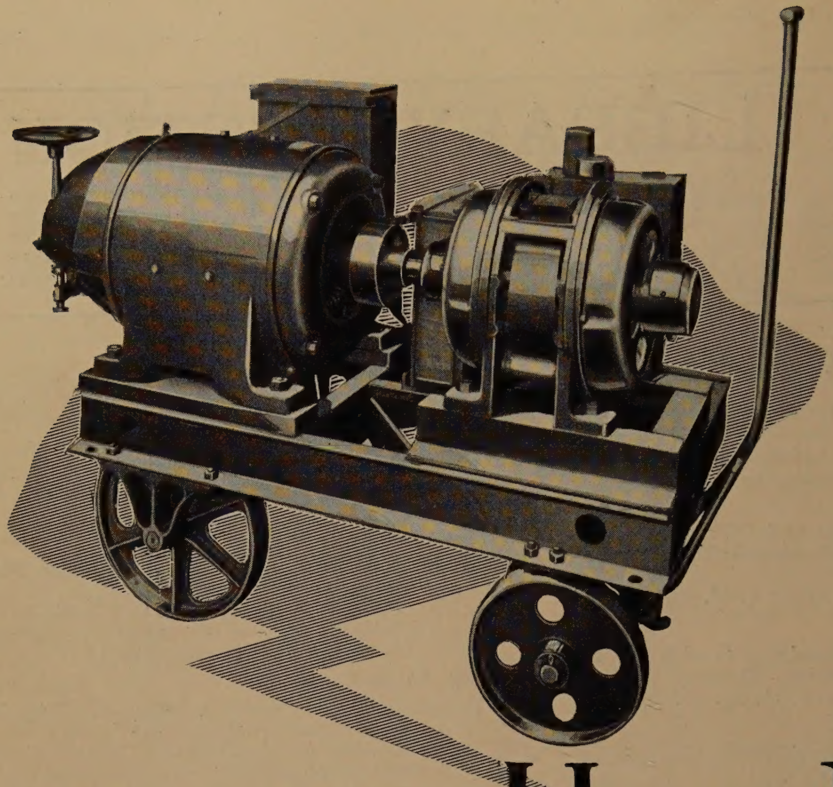
Electric Arc and Oxy-Acetylene Welding. E. Arthur Atkins. 316 pp., 1923, N. Y., Isaac Pitman & Sons.

Electro-Chemistry Related to Engineering. W. R. Cooper. 136 pp., 1923, N. Y., D. Van Nostrand Co.

Foibles and Fallacies of Science. Daniel W. Hering. 294 pp., 1924, N. Y., D. Van Nostrand Co.

Low Temperature Carbonization. S. N. Wellington and W. R. Cooper. 238 pp., 1924, Phila., J. B. Lippincott Co.

Pulverised Fuel. W. Francis Goodrich. 215 pp., 1924, Phila., J. B. Lippincott Co.



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